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**Australian Government**  
**Department of Defence**  
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# Review of Hull Structural Monitoring Systems for Navy Ships

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**Maritime Platforms Division**

Defence Science and Technology Organisation

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## **ABSTRACT**

At the request of DMO Head Maritime Systems Division (HMSD) a study was undertaken to investigate issues related to installation of hull structural monitoring systems (HSMS) on RAN ships. This report provides results of a literature and internet survey to determine the state of the art of HSMS on commercial and military ships together with discussion of issues related to navy ships generally. System configurations range from basic installations intended to monitor hull girder bending stresses up to complex developmental systems employing technologies such as fibre-optic sensors and wireless data transmission. Vendor material related to commercial off the shelf (COTS) systems is provided in a number of appendices.

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# **Review of Hull Structural Monitoring Systems for Navy Ships**

## **Executive Summary**

The 2011 Rizzo Plan to reform RAN ship repair and management practices outlined a number of reform themes including: Life Cycle Management, Risk Management Framework and Engineering Function. A number of Life of Type Evaluation studies were subsequently commissioned by the Defence Materiel Organisation (DMO). The Defence Science and Technology Organisation (DSTO) was tasked to investigate options for the structural monitoring of RAN ships as a method for determining their remaining fatigue life and a client report was delivered to the DMO Head Maritime Systems Division in November 2012. This present report builds on that work to provide a more general review of the technical aspects of hull structural monitoring systems with consideration of the differences between installations on navy ships as compared to commercial ships.

There has been little change in the basic configuration of hull structural monitoring systems for commercial ships since the International Maritime Organization (IMO) originally introduced requirements in 1994. Details of Commercial Off The Shelf (COTS) systems obtained from vendors are provided in individual appendices. The avoidance of excessive structural loading and fatigue damage as a result of operational response to overload warnings provided by these systems are cited as delivering improved safety and reduced through life cost benefits.

Military off the shelf installations typically have enhanced configurations of commercial off the shelf systems, the majority using fibre-optic sensors and networks. Fibre-optic systems potentially offer a number of advantages for navy installations as they are lightweight, high speed, are not affected by electromagnetic interference and require no re-calibration once installed. Specialist expertise is however required for their installation. Wireless communications, originally developed for monitoring of civil structures, have been demonstrated as a potential low cost solution for data communications but the ability of these systems to survive the harsher marine environment is not yet proven. Distributed accelerometer systems to detect decay of slam induced whipping oscillations are being developed. The use of acoustic emission systems targeted at potential fatigue 'hot spots' areas has been suggested as a viable approach for future navy ships.

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Navy vessels can expect to obtain similar benefits from HSMS as those gained from installation on merchant ships (such as improved safety, reduced through life costs and greater understanding of hull loads). The reliability of fatigue assessments is improved if monitoring is introduced as early as possible in the life of the ship, and ideally before it has entered service. For older ships nearing the end of their service life the major benefit of structural monitoring is to provide hull overload warnings, so long as the load capacity of the hull can be reliably determined. The inclusion of hull condition monitoring system requirements for future warship acquisitions is recommended, however it must be supported by information management and engineering resources. For the RAN, these outcomes relate directly to Life Cycle and Risk Management themes from the Rizzo Review recommendations.

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# Contents

## ACRONYMS & ABBREVIATIONS

|   |           |
|---|-----------|
| <b>1. INTRODUCTION.....</b>                                 | <b>1</b>  |
| <b>2. SHIP STRUCTURAL LOADING .....</b>                     | <b>1</b>  |
| 2.1 Static Loads .....                                      | 2         |
| 2.2 Low Frequency Dynamic Loads .....                       | 2         |
| 2.3 High Frequency Dynamic Loads.....                       | 2         |
| 2.4 Impact Loads.....                                       | 3         |
| 2.5 Operational Loads.....                                  | 3         |
| 2.6 Thermal Loads .....                                     | 3         |
| <b>3. STRUCTURAL RESPONSE.....</b>                          | <b>4</b>  |
| 3.1 Overload Failure .....                                  | 4         |
| 3.2 Fatigue Failure .....                                   | 5         |
| 3.2.1 Hull Girder Fatigue Life .....                        | 5         |
| 3.2.2 Local Structural Fatigue.....                         | 6         |
| 3.2.3 Fatigue of Warships .....                             | 6         |
| <b>4. HULL STRUCTURAL MONITORING OVERVIEW .....</b>         | <b>7</b>  |
| 4.1 Regulatory Influences .....                             | 8         |
| 4.2 Typical HSMS Configuration.....                         | 9         |
| <b>5. REVIEW OF EXISTING HSMS.....</b>                      | <b>10</b> |
| 5.1 Commercial off the Shelf Systems .....                  | 10        |
| 5.2 Military off the Shelf .....                            | 11        |
| 5.2.1 French Navy (Marine Nationale) .....                  | 11        |
| 5.2.2 Royal Norwegian Navy .....                            | 15        |
| 5.2.3 United States Coast Guard .....                       | 16        |
| 5.3 Developmental Systems .....                             | 17        |
| 5.3.1 Defence Evaluation and Research Agency .....          | 17        |
| 5.3.2 Armidale Class Patrol Boat Concept Demonstrator ..... | 18        |
| 5.3.3 FSF-1 SEA FIGHTER.....                                | 19        |
| 5.3.4 RV TRITON .....                                       | 20        |
| 5.3.5 Acoustic emission monitoring .....                    | 21        |
| <b>6. HSMS TECHNOLOGIES .....</b>                           | <b>22</b> |
| 6.1 Strain Gauges.....                                      | 22        |
| 6.1.1 Long Base Strain Gauges .....                         | 22        |
| 6.1.2 Short Base Strain Gauges.....                         | 23        |
| 6.1.3 Strain Gauge Temperature Compensation .....           | 25        |
| 6.2 Slam Monitoring .....                                   | 26        |

|       |                                      |    |
|-------|--------------------------------------|----|
| 6.3   | Data Communication .....             | 27 |
| 6.4   | Data Processing and Management ..... | 28 |
| 6.5   | Human-System Interface.....          | 28 |
| 7.    | HSMS FOR NAVY SHIPS.....             | 29 |
| 7.1   | Key Benefits.....                    | 30 |
| 7.1.1 | Operational Warnings .....           | 30 |
| 7.1.2 | Through Life Costs.....              | 30 |
| 7.1.3 | Integration with Other Systems ..... | 30 |
| 7.1.4 | Improved Designs .....               | 31 |
| 7.2   | System Configuration .....           | 31 |
| 7.2.1 | Monitoring Parameters.....           | 31 |
| 7.2.2 | Installation.....                    | 31 |
| 7.2.3 | Hull Girder Monitoring .....         | 32 |
| 7.2.4 | On-Board Fatigue Prediction .....    | 34 |
| 8.    | CONCLUSIONS.....                     | 34 |
| 9.    | ACKNOWLEDGEMENTS .....               | 36 |
| 10.   | REFERENCES .....                     | 36 |
| 11.   | LIST OF APPENDICES.....              | 40 |

## Acronyms & Abbreviations

|                 |  |
|-----------------|--|
| <b>ACPB</b>     | Armidale Class Patrol Boats  |
| <b>BPC</b>      | French amphibious assault ship (Bâtiment de Projection et de Commandement) |
| <b>C-Mn</b>     | Carbon - Manganese   |
| <b>COTS</b>     | Commercial Off The Shelf   |
| <b>DE&amp;S</b> | Defence Equipment and Support  |
| <b>DERA</b>     | Defence Evaluation and Research Agency                                     |
| <b>DMO</b>      | Defence Materiel Organisation  |
| <b>DNV</b>      | Det Norske Veritas   |
| <b>DSTO</b>     | Defence Science and Technology Organisation                                |
| <b>DWT</b>      | Deadweight tonnage   |
| <b>ESHHM</b>    | Extended Ship Hull Health Monitoring                                       |
| <b>EU</b>       | European Union   |
| <b>FEA</b>      | Finite Element Analysis  |
| <b>FFI</b>      | Norwegian Defence Research Establishment                                   |
| <b>FRP</b>      | Fibre Reinforced Plastic   |
| <b>FSF</b>      | Fast Sea Frame   |
| <b>GPS</b>      | Global Positioning System  |
| <b>GUI</b>      | Graphical User Interface   |
| <b>HMAS</b>     | Her Majesty's Australian Ship  |
| <b>HMSD</b>     | Head Maritime Systems Division   |
| <b>HNOMS</b>    | His/Her Norwegian Majesty's Ship   |
| <b>HSI</b>      | Human-System Interface   |
| <b>HSMS</b>     | Hull Structural Monitoring System(s)                                       |
| <b>Hz</b>       | Hertz  |
| <b>IACS</b>     | International Association of Classification Societies                      |
| <b>IMO</b>      | International Maritime Organization  |
| <b>JIP</b>      | Joint Industry Program   |
| <b>kHz</b>      | Kilohertz  |
| <b>LBSG</b>     | Long Base Strain Gauge   |
| <b>LDT</b>      | Linear Displacement Transducer   |
| <b>LOTE</b>     | Life of Type Evaluation  |

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|                |   |
|----------------|---|
| <b>LVDT</b>    | Linear Variable Differential Transformer                            |
| <b>m</b>       | Metre(s)  |
| <b>MARPOL</b>  | International Convention for the Prevention of Pollution From Ships |
| <b>MCM</b>     | Mine Counter Measures   |
| <b>MEMS</b>    | Micro-Electro-Mechanical Sensor                                     |
| <b>MoD</b>     | Ministry of Defence   |
| <b>MOTS</b>    | Military Off The Shelf  |
| <b>MPa</b>     | Megapascal  |
| <b>NATO</b>    | North Atlantic Treaty Organisation                                  |
| <b>NSWCCD</b>  | Naval Surface Warfare Center, Carderock Division                    |
| <b>ONR</b>     | Office of Naval Research  |
| <b>PC</b>      | Personal Computer   |
| <b>RAN</b>     | Royal Australian Navy   |
| <b>RNZN</b>    | Royal New Zealand Navy  |
| <b>RNoN</b>    | Royal Norwegian Navy  |
| <b>SBSG</b>    | Short Base Strain Gauge   |
| <b>SHHM</b>    | Ship Hull Health Monitoring   |
| <b>S-N</b>     | Stress – No. of Cycles  |
| <b>SOLAS</b>   | International Convention for the Safety of Life at Sea              |
| <b>SPDAS</b>   | Scientific Payload Data Acquisition System                          |
| <b>SSC</b>     | Ship Structures Committee   |
| <b>UK</b>      | United Kingdom  |
| <b>USCG(C)</b> | United States Coast Guard (Cutter)                                  |
| <b>US(N)</b>   | United States (Navy)  |
| <b>WHEC</b>    | High Endurance Cutter   |

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# 1. Introduction

The early decommissioning of the Royal Australian Navy (RAN) ship HMAS MANOORA, the extended unavailability of HMAS KANIMBLA and the temporary unavailability of HMAS TOBRUK in 2011 prompted the Government to appoint an independent team to develop a plan to reform RAN ship repair and maintenance practices. This resulted in the delivery of the Rizzo Review [1] which outlined a number of reform themes including: Life Cycle Management, Risk Management Framework and Engineering Function.

A number of Life of Type Evaluation (LOTE) studies were subsequently commissioned by the Defence Materiel Organisation (DMO) in relation to RAN surface fleet vessels and reportedly a common recommendation across the studies\* was for the installation of fatigue life monitoring systems on each Class of ship. At the RAN Maritime Science and Technology Conference 2012, DMO Head Maritime Systems Division (HMSD) requested advice from DSTO in relation to options for the structural monitoring of RAN ships as a method for determining their remaining fatigue life [2].

The use of hull structural monitoring systems (HSMS) on navy ships is seen as a potentially effective way in which to:

- Provide real-time guidance of loading information and trends and to warn of extreme loading events so that risk of structural overload may be avoided, and to
- Obtain actual in-service information of the extreme and long term fatigue loads to which the ships are exposed so that this can be used for improvements in both the design and the through life management of ship structures,

These outcomes relate directly to Life Cycle and Risk Management themes from the Rizzo Review and their successful outcomes are very much dependent on the support of a strong Engineering Function. It is therefore seen as a potentially effective way in which to address the Rizzo Review recommendations.

A restricted distribution DSTO Client Report providing RAN specific advice in relation to hull structural monitoring and fatigue was delivered to HMSD in November 2012. This present report builds on that work to provide a more general review of the technical aspects of HSMS so that this may inform engineering decisions related the installation of HSMS on navy ships.

# 2. Ship Structural Loading

In order to address the subject of hull structural monitoring it is first necessary to look at the types of hull loading and the subsequent structural responses to which it may be relevant. A number of different loading types contribute to the potential for hull failure through overload or fatigue; overload results from an extreme loading event that exceeds the load carrying capacity of the structure, whereas structural fatigue results from the accumulative damage effect of cyclic loading on the structure.

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\* Not all reports resulting from these studies are available to the authors.

## 2.1 Static Loads

The static loads acting on a ship's structure are those due to the differences between the weight and buoyancy distributions along the ship. The weight of items such as the ship's structure, machinery, outfit, fuel and cargo are not distributed uniformly along the length of the ship. The weight of the ship is counteracted by the buoyancy force of the water displaced by the ship when the ship is afloat. The differences between the weight and buoyancy cause shear forces and bending moments along the ship and are often referred to as 'still water loads'. Whilst these can remain relatively constant over a ship's lifetime (at least in the case of warships such as frigates and destroyers) they can significantly influence structural fatigue as the mean stress level affects crack growth rate. Cargo weight variations in bulk carriers and tankers can generate large loads that contribute to low-cycle fatigue and, in the extreme, can cause overload and collapse of the hull girder. Whilst the risk of this form of overload is generally lower, navy ships such as replenishment and logistic support ships that carry large cargoes are also subject to significant still water bending load variations. Hull monitoring can be used to monitor bending moment variations due to cargo loading, but it does not measure the actual still water stresses; the mean stress levels must be determined analytically to be included in the assessment of overall stress levels.

## 2.2 Low Frequency Dynamic Loads

Low frequency cyclic loads are imparted on the hull through the action of the waves on the ship as it moves through the ocean. These include the pressure acting on the hull due to the wave profile and the inertial reactions to the accelerations caused by the ship's motions. These are referred to as 'wave loads' and together with still water loads are the 'primary' hull girder loads. Extreme wave events can potentially cause hull collapse and the use of hull monitoring enables the magnitude of wave bending loads to be monitored and warnings to be provided to help ensure that loads do not reach dangerous levels. This is generally cited as one of the key benefits of HSMS and is relevant to both merchant and navy ships.

Wave loads are the major contributor to hull fatigue and tend to increase linearly with wave height in low to moderate sea conditions, but vary non-linearly in higher sea states. Hull fatigue estimates are generally based on numerical load predictions using seakeeping software codes to predict wave loading. These predictions are less reliable in higher sea states when non-linearities become more important. It is noted by the Ship Structure Committee [3] that "nonlinearities in the response of ships to waves can have a significant effect on predictions of maximum lifetime loads (but they) have less effect on the loads for fatigue analysis because the majority of the loading that causes fatigue damage comes from repeated application of low amplitude loads, which are more linear in nature". This may be less true for navy ships that are frequently driven at high speed as the Ship Structure Committee [3] also notes that wave-induced whipping is an exception to the statement on the importance of non-linearities on fatigue as it significantly increases the number of fatigue loading cycles (see also Section 2.4). The use of HSMS establishes a record of the actual stress cycles that the ship experiences and with monitoring over time and across a number of similar vessels can be used to improve the fatigue loading predictions.

## 2.3 High Frequency Dynamic Loads

The high frequency dynamic loads are those that may induce a vibratory response in the ship structure. These loads become significant if the frequency of the load is close to the natural



frequency of the ship's hull, resulting in amplification of the load due to resonance. Examples of high frequency dynamic loads include springing caused by the ship encountering waves at a frequency near the ship hull natural frequency and the loads caused by large unbalanced rotating machinery. If springing is a regular occurrence then it will be a significant contributor to fatigue as the frequency of loading (and so number of cycles) is greatly increased. On larger ships the natural hull girder frequency is typically in the range 1 – 2 Hertz [3], whereas for warships such as frigates and destroyers this is slightly higher. Hull monitoring will generally be able to detect such incidents if the sampling rate of strain sensors is sufficiently high, e.g. 15-20 Hz is typically required [4].

## **2.4 Impact Loads**

Bow slamming is the result of the bow emerging from one wave crest and then re-entering with significant impact (slamming) into the next wave. This can impart significant local impact loads and cause hull girder whipping; nonlinear, high frequency hull vibrations that last for around 5-10 cycles [3] at a frequency near that of the hull's natural frequency. These whipping responses are superimposed on the low frequency wave load responses (Section 2.2) and significantly increase the number and magnitude of hull girder fatigue loading cycles. Slamming is particularly relevant for high speed vessels where the frequency and magnitude of slamming is greatly increased at higher speeds.

The peak slam bending moment is generally not detected by hull monitoring strain gauges unless sampled at sufficiently high frequencies; typically at least 100 Hz is needed but up to 500 Hz and possibly higher may be needed [4]. The transient whipping decay is detectable by strain gauges and accelerometers with sufficiently high sampling rates and is used in some instances to warn of slamming (see Section 6.2).

## **2.5 Operational Loads**

Operational loads are those that arise due to the ship performing specific activities. In the case of naval vessels, these can include loads due to the landing of helicopters, the sloshing of fluids in large tanks and weapons firing effects. These effects are usually relatively localised but associated hull girder vibration may be detected as hull girder stresses through hull monitoring. Local monitoring for these effects requires significantly higher sampling frequencies, up to 3 kHz [4] and is usually only needed if the frequency or magnitude of stresses is expected to be high.

## **2.6 Thermal Loads**

The importance of thermal stressing of ships has been recognised for a long time and a comprehensive discussion and a review of methods for determining thermal stresses was provided by Hechtman in 1956 [5] where he noted that:

“A distinction should be made between the strains arising from a change in temperature and the strains resulting from external loads. In the latter case, the stresses are proportional to the strains. By contrast, thermal stresses arise when the thermal strains are inhibited. It is important to recognize that the thermal strains observed in ships represent the free expansion part of this process and cause no stress but rather are manifested in elongation and bending of the hull. When considered together with the temperature distributions, the measured thermal strains can be used to determine the amount of thermal strain which has been

prevented from occurring by the rigidity of the surrounding structure. This amount determines the actual thermal stress”

Thermal stresses will then arise as a result of a non-uniform temperature distribution throughout the hull and their magnitude will be affected by the degree of restraint provided by the surrounding structure. Stresses will also arise in instances where materials have different thermal expansion coefficients, e.g. steel hull with aluminium superstructure.

In regards to hull structural monitoring, the important issue is that thermal strains will be measured by the strain gauges and these must be eliminated from the measurements so that they do not provide a false indication of stresses in the hull material. Additionally, strain gauges themselves are sensitive to thermal effects and temperature compensation is required (see Section 6.1.3).

### 3. Structural Response

As a result of the applied loading, the ship's structure will respond at different levels, with potential failure modes ranging from the global hull-girder level down to the local detail level. The mechanisms through which these failures occur are usually quite different and the consequences vary greatly, from small nuisance level fatigue cracking through to overall collapse of the hull girder under extreme loads.

#### 3.1 Overload Failure

Overload is typically characterised by an initial onset of plate and/or panel buckling under compressive loading, brought about through improper loading practices or extreme wave loading events. There may be a number of different loading scenarios that can cause such failures, collectively termed 'limit states' and safe load levels must be set accordingly. The use of HSMS enables actual loads to be monitored in real time and to provide warnings so that these limit states may be avoided with an appropriate level of safety margin.

Buckling behaviour is heavily influenced by the geometry of the structure, more so than by the yield strength of the material, and so calculation of different potential buckling modes and ultimate strength of individual structures is needed to ensure that appropriate limit states are defined for monitoring systems. The importance of establishing these limits states for structural monitoring of warships should not be underestimated. Although the hull girder of warships is relatively stiffer than large merchant ships (higher natural frequency), warships are more lightly framed and more prone to plate and panel buckling. The ultimate strength is also significantly influenced by geometric imperfections, such as weld distortion which is more pronounced in warships, and appropriate allowances must be included in ultimate strength calculations. Elastic properties of structural materials have an important influence on the ultimate strength and there has been a growing focus on this in the literature as a result of the increased use of aluminium in ship construction (e.g. Magoga and Flockhart [6]). The role of the Engineering Function needed to undertake these analyses is evident.

## 3.2 Fatigue Failure

Structural fatigue on the other hand is essentially a local phenomenon that is associated with fracture under predominantly tensile loading. Fatigue damage accumulates with each loading cycle and the occurrence of fatigue cracking in ship structures is almost inevitable, with the rate of occurrence typically increasing with age. This has led to the notion of ‘fatigue life’ of a ship’s structure, so it is worthwhile to firstly establish what the term actually means.

### 3.2.1 Hull Girder Fatigue Life

At the hull girder level, fatigue life is based on the concept that the hull girder can be treated as a simple beam to establish if there is adequate section modulus to safely withstand the cyclic wave bending and other loads acting on the ship. The fatigue endurance limit of this simple beam is then fundamentally a function of the stress induced by loading, the number of loading cycles to which it is exposed and the fatigue behaviour of the structural material.

Hull girder fatigue calculations are based on the assumed lifetime loading profile and cross sectional properties of the hull girder, typically calculated for a number of sections along the hull. The well-known Palmgren-Miner linear damage hypothesis is used together with S-N (Stress Range – No of Cycles) curves for welded structures to establish the fatigue life for each hull girder section. An example of a typical S-N Curve for base material<sup>†</sup> and welded joints from Det Norske Veritas (DNV) [7] is shown in Figure 1.

Ship fatigue design rules and guidelines are well documented in various Classification Society Rules for navy ships. There are however some differences across these rule sets and it is important that the chosen rule set is applied completely and consistently so that results are not invalidated. For example there may be differences in relation to:

- i. Allowances (or corrections) needed for a number of factors that influence the fatigue endurance such as mean stress levels, the direction of loading relative to the weld and the environment. Material yield strength has an effect on the fatigue behaviour of unwelded components (e.g. plate edges) but has little influence on crack initiation in welded structures [8]. Although generally based on the same basic form of S-N curve, different correction methods are used by the various classification societies.
- ii. Methods for development of the lifetime loading profile which can vary from the use of a simple rules based formulation to the application of seakeeping analysis for calculation of the loading distribution from first principles,
- iii. Methods for the calculation of section modulus and the treatment of significant openings, structural discontinuities and longitudinally ineffective structure that is to be omitted from the section calculations,
- iv. Allowances for the effects of corrosion are usually considered through simple plate thickness reductions when calculating the section modulus for hull girder fatigue assessments, but approaches and values vary across different rule sets.

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<sup>†</sup> Defined as “C-Mn steels, duplex and super duplex steels and austenitic steels with yield stress less than 500 MPa”.

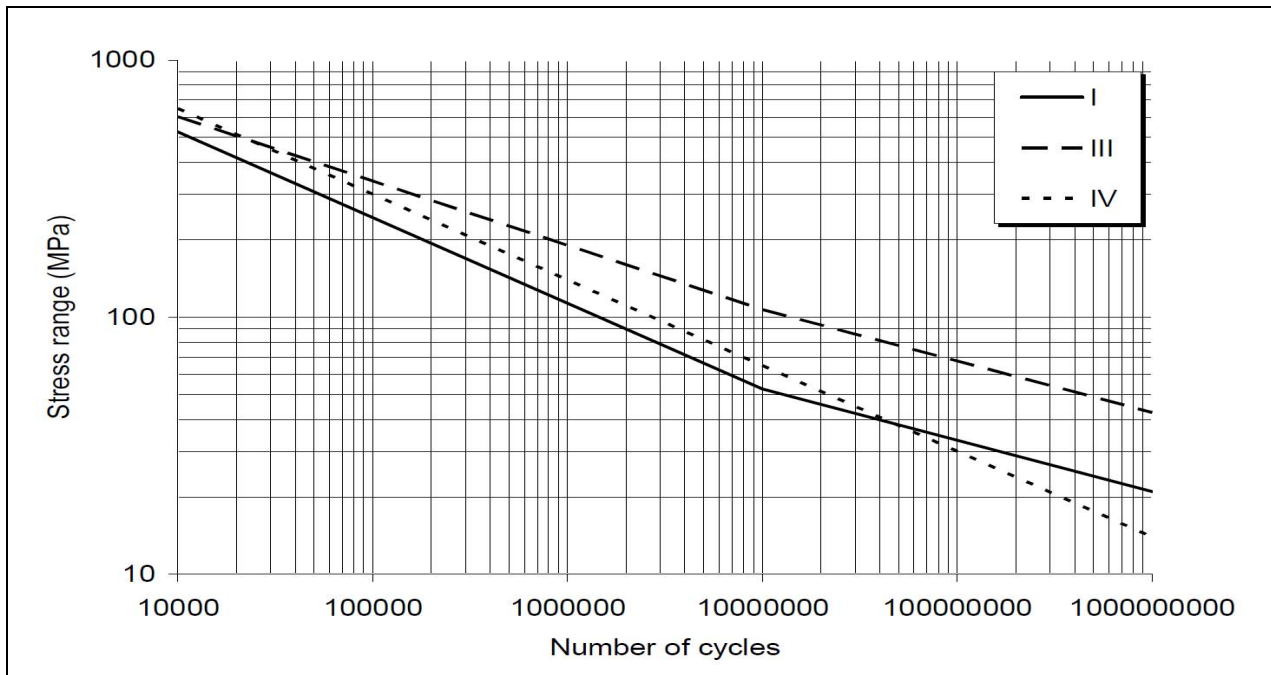


Figure 1. DNV Basic Design S-N Curve (I = Welded Joint, III = Base Material in Air, IV = Base Material in Corrosive Environment) [7].

### 3.2.2 Local Structural Fatigue

Warship hulls are complex structures and do not fail in fatigue as would a simple beam; rather failure initially occurs at local structural components where stress concentrations are caused through changes in section and welding. Residual stresses are introduced into the structure during construction through welding, rolling and other manufacturing practices and have a significant effect on fatigue behaviour. Classification Society rules and other standards for detailed fatigue design are based on statistical analysis of the results from testing of relatively small, welded structures that inherently include some, but not all, of these effects. Based on these results and depending on the direction of loading and how fatigue cracking is likely to initiate, a welded joint will typically be classified into one or more of a number of welded joint detail classes for fatigue assessment purposes. Different S-N curves are given for each joint detail class.

Stress ranges relevant to the structural detail are generally obtained through finite element analysis (FEA) of the larger structural assembly, possibly of the whole ship, and with consideration of a number of different load cases. High, localised stresses identified by FEA, so-called 'hot spot' stresses, are used together with the relevant S-N curve to establish the fatigue life of the joint. Procedures for calculation of the fatigue life of structural details may vary somewhat in their approach to determining the 'hot spot' stress (e.g. see Maddox [9]) and the corrections that are used for mean stress and other influences. It is important therefore that a complete and consistent set of rules is used when undertaking such analysis.

### 3.2.3 Fatigue of Warships

The economic viability of maintaining warships is becoming increasingly more important and in his review of this report Snell [10] suggested that the definition of fatigue life for a ship can be associated with the frequency and cost of repairs verses the cost of replacing the ship, which intuitively should increase as the ship gets older and eventually it will no longer be economically viable to maintain the ship in service. The relatively high cost of a new warship and the lost

revenue cost associated with maintenance stand down for a commercial ship means that this point of economic un-viability usually comes later for the warship. The ability to understand the influence of fatigue on the continued economic viability of a warship is clearly an important consideration, but for a warship is somewhat more difficult to define.

Warships are typically very structurally complex and fatigue cracking, which is very dependent on the structural detail design, can occur at virtually any time in the life of a ship. The usual treatment in both commercial and navy ships is for fatigue cracks to be weld repaired at the earliest possible opportunity and in problematic cases this may also include design modifications to improve fatigue performance. Novel repair methods such as the use of composite patching are also becoming more common. The outcome of these repairs and modifications is that the fatigue life of that particular detail is to some extent reinstated and with each additional change the predicted fatigue life of the ship becomes increasingly more difficult to define; and even more so in structurally complex warships.

Fatigue is significantly complicated by the presence of corrosion, which causes stress concentrations, removes structural material and can affect the development and growth of cracks in the material. The likelihood and rate at which corrosion occurs can also be expected to increase with the age of the ship and the repair of corrosion damage may ultimately become a more significant influence on the economic viability of the ship than fatigue. Although modern protective coatings are quite effective in preventing corrosion they are subject to damage and degradation and an effective inspection and maintenance system is needed to ensure that corrosion does not become a significant factor in consideration of economic viability.

In warships, physical access to repair both fatigue and corrosion damage is usually constrained and repairs are relatively more expensive due to space and equipment interference restrictions. Knowledge of the wave loading and the resulting stresses in the ship's hull are essential for reliable fatigue assessments and the only way to obtain actual data for a particular ship is through the use hull and environment monitoring over the life of the ship. The use of hull monitoring in the vicinity of high stress areas provides detailed knowledge of the stress history and helps to warn of likely failures and the effects of any subsequent modifications. The operational life of warships is also subject to other influences such the ability to fulfil particular operational directives, strategic environment and the consequences of government policy that may result in mothballing, early retirements or life of type extensions. There is a need for a clear understanding of the material condition of the ship to support these decisions and this understanding can be significantly enhanced if reliable hull stress and loading information is available. For these and other reasons, such as the benefits that are associated with reduced loading of the hull due to improved operator guidance, the inclusion of hull condition monitoring systems with future warship acquisitions is seen as highly beneficial in the long term however it must be supported by information management and engineering resources.

## **4. Hull Structural Monitoring Overview**

The minimum aim of HSMS is to measure global hull girder stresses, to compare these to previously established safe (reference) levels and to provide warnings if these levels are exceeded. Detection of bow emergence and slamming using accelerometers or pressure gauges is used together with strain gauge information to provide on-board guidance of the loading of the hull and warnings of the need for corrective action if necessary. Ongoing recording and analysis

of data provides the basis for establishment of accurate loading profiles and fatigue life predictions that may be used to improve maintenance practices and economic life assessments.

## 4.1 Regulatory Influences

Whilst not mandatory for ships of war to comply with the International Maritime Organization (IMO) Conventions, there is an increasing trend by navies to do so as far as is practical, particularly in regards to the MARPOL [11] and SOLAS [12] conventions. Adoption of regulations such as SOLAS (Chapter V, Reg 20) requires that ships over 500 gross tonnes<sup>‡</sup> and engaged in international voyages have voyage data recorders installed; these are the marine equivalent of the aircraft “black box flight recorder”. The implementation of the specific rules relating to adequacy of structure and equipment are referred to the International Association of Classification Societies (IACS) and to individual Classification Societies. Following the loss of a number of ships in the 1980s and early 1990s, Classification Societies have established requirements for the fitting of HSMS in certain ships and there is an increasing trend to interface and merge voyage data recorders with hull monitoring systems, e.g. Forestier and Austin [4]. Kim and Kim [13] note that HSMS have been recommended by IMO and IACS for use on bulk carriers of 20,000 tonnes deadweight<sup>§</sup> (DWT) and above since 1994 and more recently for tankers and LNG carriers. Classification Societies offer additional Class notations for ships that have these systems installed.

The Classification Society rules covering hull monitoring systems share some common themes. The first of these is the intent of these systems, which is twofold:

- i. To provide the vessel’s Master and officers with real-time data on the stresses that the ship is experiencing, and
- ii. To provide data for analysis at a later date.

A second common theme is the type and arrangement of the sensors that are required as part of a HSMS and the basic arrangement has become relatively standardised (see Section 4.2).

The third common theme of the Classification Society rules is the documentation that is required to be approved by the Society. Generally, approval requires the submission of sensor specifications (if not type approved), system block diagram, sensor calibration procedures, structural analysis (e.g. FEA) to justify the placement of strain gauges, along with system user manuals and fault detection processes. Any modifications that would need to be performed on the ship’s structure (e.g. hot work) will also need to be approved by the Classification Society.

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<sup>‡</sup> The size of navy ships is generally referred to in displacement, which is their actual weight, whilst merchant ships are referred to in terms of Gross Tonnage (GT) as defined by IMO [14]:  $GT = K_1 V$ , where:  $V$  = total volume of all enclosed spaces in the ship in cubic metres and  $K_1 = 0,2 + 0,02 \log_{10} V$ . Lloyd’s Naval Ship Rules [15] notes that  $V$  includes gun turrets, radar domes, masts, etc.

<sup>§</sup> Deadweight is the total variable weight content of a ship, such as cargo, fuel, stores and any other variable item that the ship can carry.

## 4.2 Typical HSMS Configuration

The Classification Society influence has led to HSMS becoming relatively standardised; the minimum requirement is for two strain gauges on the weather deck at amidships, an accelerometer or pressure transducer in the bow and a data processor and graphical user interface (GUI) on the bridge. A more typical configuration with four long-base strain gauges (LBSGs) is however illustrated in Figure 2. In this configuration, the LBSGs are installed on top of the main deck at amidships (port and starboard) and at the quarter lengths of vessels for monitoring of hull girder stress (one side only). Strains are converted to stresses (using Hooke's Law) with the inherent assumption that the midships measurements of strain on both sides of the deck permits the estimation of both the vertical and horizontal bending components (through the average of the combined sum or difference respectively) and that torsional strains are "estimated by computation for given sea states" [13]. This information can be used to infer the 'fatigue life' of the hull girder using simple beam theory (see further discussion in Section 3.2). It is emphasised that this configuration is for a prismatic commercial bulk cargo ship and may have limited application for many naval vessels where space for equipment and sensors is more limited and the inference of stress throughout the structure is far more challenging as a result of their more complex structures and load paths.

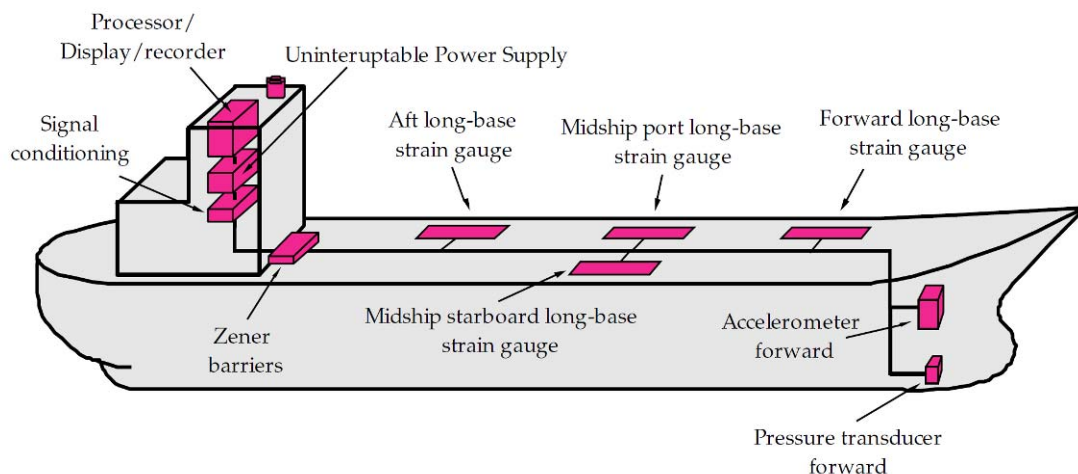


Figure 2. Typical HSMS configuration for bulk carrier or tanker (Lloyds Register [16])

Accelerometers and pressure sensors are located in the bow to measure slamming incidents, bow emergence and slamming pressures. On larger vessels where the deckhouse and bridge are located aft, the occurrence of slamming is not readily noticeable to the crew and it is particularly important that slamming be monitored and warnings be displayed on the bridge as it is a source of high structural loading and a significant contributor to structural fatigue (Section 2.3. Commercial HSMS (Section 5.1) typically undertake cycle-counting of measured stresses using the so-called 'rain-flow counting method' and use simple hull girder fatigue assessment methods (as described in Section 3.2.1) to provide real-time estimates of fatigue damage accumulation and remaining hull girder fatigue life. The use of hull monitoring for avoidance of slamming has therefore proved to be of major benefit to commercial ship owners.

More comprehensive HSMS extend to fully integrated systems, capable of transmitting and storing data, with multiple sensors including strain gauges at a variety of locations,

accelerometers/motion sensors, bow pressure sensors, sea state/environmental sensors and navigation (GPS, speed, gyro compass, rudder angle, etc.) sensors. Wave and ship motions monitoring is needed for provision of operator guidance (e.g. for boat and helicopter operations) and weather forecast information can be used to assist voyage planning.

## 5. Review of Existing HSMS

In 1959 the Ship Structure Committee [17] recommended a research program to “obtain statistical records of vertical longitudinal wave bending moments experienced by various types of ships operating on different trade routes, with the emphasis being placed on extreme values of external loads”. The expected outcome of this program was that “After five or more years, statistically valuable information on extreme loads for different services and different ship types should emerge”. Now over 50 years later hull monitoring is common place and a literature and internet survey has been carried out to identify the current state of the art of HSMS. This review has identified systems that for this report can be grouped into three categories:

- i. Commercial off the shelf (COTS) systems. These are systems that have been developed by industry for industry clients.
- ii. Military off the shelf (MOTS) systems. These are COTS based systems that have been installed on military ships. There may be developmental or research components in addition to the base MOTS system and they are developed jointly by industry and military.
- iii. Research systems. These are one-off systems that are being developed and trialled, quite often on navy ships.

Regardless of the categorisation, all HSMS must be configured specifically for the ship to which they are fitted and so there is some level of customisation and the distinction between one category or another is sometimes not entirely clear cut.

### 5.1 Commercial off the Shelf Systems

A number of COTS HSMS were identified and these are listed in Table 1. Systems that do not provide strain measurement and only monitor ship motions for voyage planning have not been included. All systems listed have Class approval by at least one IACS Classification Society and brief comments regarding each system have also been included in Table 1. Further information of each system can be found in publicity material downloaded from the internet\*\* or obtained directly from vendors, and copies are provided in Appendix A through Appendix J.

The systems listed in Table 1 are very similar in their base configuration (similar to Figure 1) and are generally able to be customised for different ship types. It is evident from a review of hull monitoring systems by the Ship Structure Committee in 1997 (Slaughter et al [18]) and comparison with those listed in Table 1, that the base configuration for COTS HSMS has not changed greatly in the past 15 years. There have however been some significant technology

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\*\* Some material has been cut, pasted and reformatted in order to suit publication of this report, but content is unchanged.



developments in relation to the type of strain gauge used and the sensor and data transmission technology and these are discussed further in Section 6.

## 5.2 Military off the Shelf

Hull monitoring of naval vessels can obtain similar benefits as merchant ships, such as operator guidance during heavy weather and improved knowledge of the long-term fatigue loading of the ships. Historically some of the earliest hull monitoring was carried out on navy ships; e.g. Smith [19] reported in 1966 that extreme-value strain records had then been obtained for more than forty British warships using mechanical strain recorders. More recently, hull monitoring of navy ships has utilised the commercial HSMS and adapted them for navy applications, giving rise to the MOTS systems. Only a limited number of recent MOTS applications were identified for this study but economic pressures and improvements in technology are likely to see the adoption of more of these systems in the future.

### 5.2.1 French Navy (Marine Nationale)

French company SIREHNA, a member of the DCNS Group, have installed monitoring systems on the French amphibious assault ships (BPC) MISTRAL and TONNERRE. The system is based on the HULLMOS<sup>®</sup> system and uses strain sensors mounted on the ship main longitudinal girders as well as two accelerometers, one in the bow and one in the stern. Similar to other systems, it includes a bridge alarm in the event that pre-defined design and operational limits are exceeded. SIREHNA have enhanced the base system with a sea-state estimation module, based on the analysis of ship responses to waves (mainly motions) to complement the system, however further information on this installation has not been obtained.

Table 1. Commercial HSMS and their respective Vendors

| System Name                       | Vendor   | Location  | Web Address  | Comments  |
|-----------------------------------|--|---|--|---|
| HMS Hull Monitoring System        | MCA Consultants  | Newport Beach, CA, USA  | www.mcaco.com  | <ul style="list-style-type: none"> <li>i. Linear Variable Differential Transformer (LVDT) LBSG strain sensors, bow accelerometer and pressure transducers for slam monitoring.</li> <li>ii. Wireless radio communication from sensors to 'command centre' available.</li> <li>iii. Class approved (multiple)</li> <li>iv. Published client list only includes tanker operators.</li> <li>v. 'Command centre' is stand alone rack that may be difficult to fit in suitable location on some combatants.</li> </ul>   |
| HULLFIB<br><br>See also (STREMOS) | Micron Optics, Inc<br><br>Global Maritime Engineering  | Atlanta, GA, USA<br><br>Busan, Korea                                    | www.micronoptics.com<br><br>www.straininstall.com            | <ul style="list-style-type: none"> <li>i. Fibre-optic LBSGs, accelerometers and pressure transducer.</li> <li>ii. Fatigue damage accumulation capability.</li> <li>iii. Trial installation of a variety of multiplexed fibre-optic sensors (strain, fire/temperature, flooding, door close and acceleration sensors on ex-USS SHADWELL in 2008.</li> <li>iv. Class approved (multiple) - expandable for additional sensors.</li> </ul>  |
| HULLMOS®                          | Main: Rouvari Oy<br><br>Other Suppliers:<br>- Sirehna<br><br>- Hydrographic & Marine Consultants (HMC) | Helsinki, Finland<br><br>NANTES, France<br><br>Almere-Stad, Netherlands | www.hullmos.com<br><br>- www.sirehna.com<br><br>- www.hmc.nl | <ul style="list-style-type: none"> <li>i. Fibre-optic based system with both LBSGs and short base strain gauges (SBSGs).</li> <li>ii. Developed during 1997-2000 under EU funded Eureka Project 1765.</li> <li>iii. Strain sensors and data communication network developed by Rouvari Oy. Sirehna developed GPS base motion sensors. Methods for on-line prediction of hull fatigue life developed at Technical Research Centre of Finland.</li> <li>iv. Class approved (multiple) - expandable for additional sensors.</li> <li>v. 20+ ship installations since 2000.</li> <li>vi. Fitted to French Navy amphibious assault ships including motions and sea-state estimation</li> </ul> |

| System Name                                       | Vendor   | Location                           | Web Address                             | Comments   |
|---|--|------------------------------------|---|--|
| Hull Stress Monitoring System                     | CPE Systems  | Abbotsford, VIC, Australia         | www.cpesys.com.au                       | <ul style="list-style-type: none"> <li>i. RAN LPAs insallation: 4 * LVDT SBSG, 1 * bow accelerometer and 1 * midships lateral accelerometer, navigation data.</li> <li>ii. System being further developed for installation on RNZN 'Protector' vessels (1x Multi-role, 2x Offshore Patrol, 4x Inshore Patrol) in 2013 to include ship transit and helicopter safe operating limits based on motions and seakeeping analysis.</li> <li>iii. Class approved (DNV).</li> <li>iv. Apparently no other installations at time of writing.</li> </ul> |
| Naviscan HSMS                                     | Korea Marine Technology Co., Ltd<br><br>Sea Structure Technology Co. Ltd | Ulsan, Korea<br><br>Daejeon, Korea | kmtec.en.ec21.com<br><br>www.sst21c.com | <ul style="list-style-type: none"> <li>i. LVDT LBSG sensors, accelerometer for slam monitoring, threshold velocity method, fatigue monitoring.</li> <li>ii. Claims to be exclusive provider for Temperature Compensation Type LBSG.</li> <li>iii. PC based - potentially expandable for additional sensors but not indicated in documentation.</li> <li>iv. Class approved (multiple).</li> <li>v. 40 ship installations (2001-2008).</li> </ul>   |
| Scimar  | BMT Scientific Marine  | Escondido, CA, USA                 | www.scimar.com                          | <ul style="list-style-type: none"> <li>i. Systems are configured to individual requirements.</li> <li>ii. Fatigue monitoring and route planning options.</li> <li>iii. Basic system measures: midships strain, roll, pitch, bow vertical acceleration and forefoot immersion depth and integrates information from engine room sensors and GPS.</li> <li>iv. Class approved (multiple).</li> </ul>   |
| SENSFIB   | Light Structures   | Oslo, Norway                       | www.lightstructures.no                  | <ul style="list-style-type: none"> <li>i. Fibre-optic based system.</li> <li>ii. Ice and sloshing loads monitoring options.</li> <li>iii. Over 100 ship installation since 2001 claimed.</li> <li>iv. Class approved (multiple).</li> <li>v. Base system used for RNoN SHHM installed on the FRP MCM ship.</li> </ul>  |
| Sh.A.M.An (Ship Advanced Monitoring and Analysis) | CETENA   | GENOA, Italy.                      | www.cetena.it                           | <ul style="list-style-type: none"> <li>i. Systems are configured to individual requirements - Sensors include strain gauges, accelerometers, inclinometers, pressure sensors and wave-meter or waveradar.</li> <li>ii. Class approved (RINA).</li> <li>iii. Recently fitted to Italian Navy European Multimission Frigate the CARLO BERGAMINI.</li> </ul>  |

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| System Name             | Vendor                      | Location          | Web Address           | Comments  |
|-------------------------|-----------------------------|-------------------|-----------------------|---|
| SMART <sup>STRESS</sup> | BMT SeaTech                 | Southampton, UK   | www.bmtseatech.co.uk  | <ul style="list-style-type: none"> <li>i. Can be configured to individual requirements and has fibre-optic option.</li> <li>ii. Complemented by SMART<sup>POWER</sup> for motions and power monitorina. Also SMART<sup>SHORE</sup>, a shore-based tool to analyse data from ships fitted with BMT SeaTech's SMART<sup>STRESS</sup> and SMART<sup>POWER</sup> systems.</li> <li>iii. Class approved (multiple).</li> </ul> |
| STREMOS                 | Global Maritime Engineering | Busan, Korea      | www.gmeng.com         | <ul style="list-style-type: none"> <li>i. Appears to be the mostly identical to HULLFIB.</li> </ul>   |
| StressAlert             | Straininstall               | Isle of Wight, UK | www.straininstall.com | <ul style="list-style-type: none"> <li>i. LVDT LBSG and LVDT or strain ring SBSG for strain measurement.</li> <li>ii. Class approved (multiple).</li> <li>iii. Over 100 ship installations claimed – mostly commercial but some naval (Singapore Navy )</li> </ul>  |

UNCLASSIFIED

### 5.2.2 Royal Norwegian Navy

Torkildsen et al [20] in 2005 provided an overview of a ship hull health monitoring (SHHM) installed on the Royal Norwegian Navy (RNoN) Oksøy/Alta-class mine counter measures (MCM) vessel the "HNOMS OTRA", a fibre reinforced plastic (FRP) Surface Effect Ship. Development of the system commenced in 1995, and included both a base and an extended system. The base system is a Light Structures SENSFIB fibre-optic system with a total of 36 strain and 8 temperature fibre-optic sensors located around the midships section, the forepeak and the wet deck between the side hull keels; the latter to monitor slamming. The system gives real-time information on both the global wave loading on the hull and the local loading in a number of selected critical areas and is presented via the GUI on the bridge, the control room and operations room. All data logged by the system is sent to Norwegian Defence Research Establishment (FFI) for further analyses and filing on a weekly basis.

The SHHM system on HNOMS OTRA was extended (ESHHM) as a prototype to include both existing ship system and purpose installed environmental and operating sensors, in order to monitor and record the environment, ship motion and operating parameters and so provide a complete picture of the parameters influencing the hull loading. This included X-band wave radar for wave height and direction measurements as well as a microwave altimeter mounted in the bow to measure the oncoming wave profile. An overview of these environmental and operating sensors is provided in Figure 3.

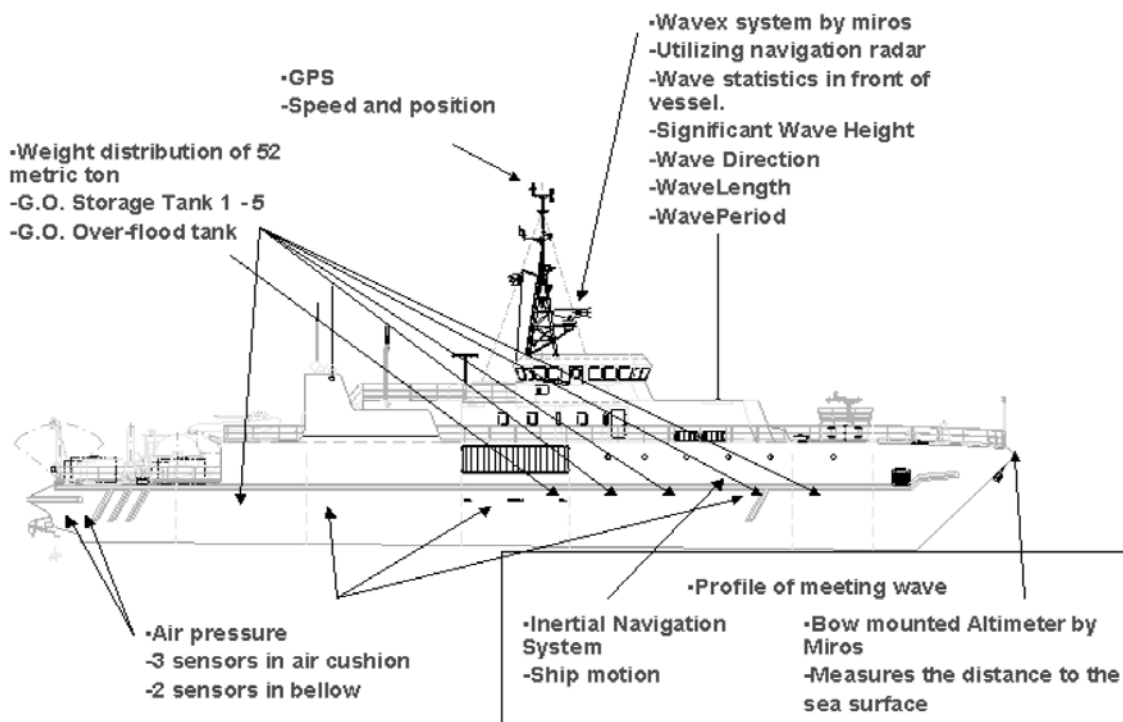


Figure 3 Overview of environmental and operating sensors on HNOMS OTRA prototype ESHHM (from Torkildsen et al [20]).

A number of comments and observations by Torkildsen et al [20] relating to the ESHHM experiences are worth reiterating as they are relevant to monitoring of navy ships.

- i. There is a need for a detailed FEA of the ship hull to determine the appropriate locations of strain sensors.
- ii. Ideally FEA should be used during the ship design stage to determine the best locations for sensors.
- iii. Wave monitoring is important to enable sea state to be correlated with the corresponding hull loading and also to establish the crew operational limits.
- iv. Ship motion sensors give information on how the sea state actually affects the ship and the interaction between ship motion and hull loads.
- v. Ship motion information is also used to correct the radar altimeter measurements to obtain the wave height in front of the vessel.
- vi. The use of fibre-optic technology to provide a number of benefits as: it is suited to harsh environments, immune to electromagnetic interference, cabling installation costs can be reduced through wavelength multiplexing and multi-fibre cables and reduced noise levels in signals compared to conventional strain gauge techniques which improve the accuracy of information outputs.
- vii. Fibre-optic hull monitoring system can be used to detect vibrations and by careful monitoring it is possible to identify noise sources and issue a warning if there is an increase in ship noise. This would require an increase in the number of sensors and the bandwidth to match the frequency spectra of the mechanical noise.
- viii. The signal processing system needs to be scalable and adaptive to enable sensors and processors to be added at a later date.

### 5.2.3 United States Coast Guard

The United States Coast Guard (USCG) has engaged in hull monitoring of ships for a number of years (e.g. see Slaughter et al [18]), and in December 2012 awarded a contract for the supply and installation of hull monitoring systems for their fleet of 378 feet 'High Endurance Cutters' (WHEC). These ships are all over forty years old, the last having been commissioned in 1971 [21] and so the monitoring systems are relatively basic and intended to provide stress level warnings only. Although this system presents a relatively straight forward installation of a COTS HSMS on a quasi-military ship, it is of interest for the following reasons:

- i. The USCG Request for Proposal [22] specifies only two midships strain gauges, to be installed below the 01 deck close to the superstructure longitudinal bulkheads<sup>††</sup>. Sampling rates of 200 Hz and 15 Hz are specified and are intended to monitor for whipping and wave bending stress respectively; there is no slam detection requirement. This minimal level of sensors required exemplifies the view that the major benefit of hull monitoring of aged ships nearing their end of life is seen to be to provide warnings of unsatisfactory stress levels.

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<sup>††</sup> This would appear to be approximately below the position of the ship's badge (crest) visible in the picture of USCGC MIDGETT (WHEC-726) shown in Figure 4

- ii. The USCG mandated the use of LBSGs in an effort to isolate hull girder membrane strains from local strain effects (see also 6.1.1).
- iii. LBSGs are typically around 2 m in length and are indicated in the Figure 2 of [22] as spanning across one transverse deck frame, on both port and starboard sides. This frame will then need to be broken and reconfigured to make way for the LBSGs. The use of alternative, shorter length gauge may perhaps have been more suitable so that breaking the frame at this critical location could be avoided.
- iv. The contract award notification gives a contract price of \$US264,184. Following a request for further advice, the USCG [23] advised that this covers the installation of up to four systems and that the successful contractor, Ward's Marine, "was determined to offer the best value to the Government and (had) exceptional past performance".



Figure 4. US Coast Guard Cutter USCGC MIDGETT (WHEC-726), (Source [24])

### 5.3 Developmental Systems

As mentioned above, some of the earliest hull monitoring was carried out on navy ships and this practice has continued. The focus of these programs has largely been to investigate issues related to the ship's structure rather than the development of new structural monitoring systems. There are exceptions however and the development of concept demonstrator HSMS have been reported in the literature.

#### 5.3.1 Defence Evaluation and Research Agency

The successful application of the extreme-value strain recorder by the Royal Navy (refer Section 5.2) was followed by the development of a new fatigue strain recorder by the Defence Evaluation and Research Agency (DERA) during the 1980s and 1990s. A detailed description of the system is provided by Brown [25] and a picture of the recorder and one of the optical gauges is shown in Figure 5. A number of innovative features of the system were: the use of an optical grating strain transducer recorder to avoid the problem of

electromagnetic interference associated with the use of conventional foil strain gauges, filtering and algorithms for the separation of wave induced and slam induced strains and the inclusion of an electronic circuit for active compensation for 'zero drift'.

With the breakup of DERA in 2001, management of the fatigue strain recorder program was passed to QinetiQ and the Ministry of Defence continued funding the program until 2009 [26]. One of these systems was also purchased by DSTO in the late 1990s and was subsequently installed for a period on HMAS ARUNTA but is no longer in service. It appears that there have been no further development of the DERA system and QinetiQ have advised that the system is no longer being produced [27].



*Figure 5. DERA wave induced fatigue strain recorder with one optical strain gauge.*

### 5.3.2 Armidale Class Patrol Boat Concept Demonstrator

A prototype hull monitoring system has been designed by DSTO and, in a collaborative project with Austal Ships, installed during ship construction of the last of class of the Armidale Class Patrol Boats (ACPB), HMAS GLENELG. The objectives of the project as outlined by Gardiner et al [28] are to:

- i. “test the application of new types of sensors, previously developed for airframe structures, in a marine application,
- ii. develop and test an open and adaptable sensor network that can easily be reconfigured for different future demands,
- iii. develop a basic understanding of the operational profile and structural performance of a high-speed, semi-planing aluminium hullform on naval patrol duties, and
- iv. provide a basis for developing a capability for structural life-assessment of the ACPB fleet, and high-speed aluminium monohulls in general.”



The initial sensor suite included micro-accelerometers and corrosion sensors developed by DSTO, Micro-Electro-Mechanical Sensor (MEMS) accelerometers, as well as standard metal-foil strain gauges, a commercial Kongsberg® Seatex MRU-6 motions sensor unit and commercial temperature and humidity sensors [28]. Two drive shaft torsion meters and a GPS were later added in a separate DSTO study to investigate the effectiveness of anti-fouling paints. At the same time a number of strain gauges were replaced as they had failed as a result of mechanical or moisture damage, some were relocated and better physical protection was provided.

The ACPB demonstrator system has been successful in achieving its objectives in a number of ways, although a number of teething problems were encountered. These include the previously mentioned strain gauge failures, system shut-downs, torsion meters failures, lost disk drives and high temperatures affecting some electronics. These have been rectified (although strain gauge failures still occur) and the system has been operational since April 2010 and has provided a great deal of valuable data which continues to be analysed. DSTO has recently licensed Associated Electronic Services Pty Ltd to commercially develop the DSTO technology, including possibly seeking Class 'type' approval of sensors.

### 5.3.3 FSF-1 SEA FIGHTER

Swartz et al [29] report on a prototype hybrid (wireless/fibre optic) system installed on the FSF-1 SEA FIGHTER (an aluminium high speed catamaran) to demonstrate the system in a realistic marine environment. The system is a hybrid in that some strain monitoring is provided through *Narada* wireless data acquisition and control units linked to a ship-board fibre-optic data network. The *Narada* units are low-cost wireless devices developed at the University of Michigan for the routine monitoring of large, complex structures such as buildings and bridges (Appendix K).

The SEA FIGHTER is an experimental littoral combat vessel fitted with a permanent monitoring system that was custom designed for the U. S. Navy. Known as the Scientific Payload Data Acquisition System (SPDAS) it is a wired system with "more than 10 tri-axial accelerometers to measure rigid-body motions, over 100 metal foil strain gauges to measure hull strains, and a wave height measurement system installed on the ship bow" [29]. The SPDAS has been in operation on the ship since 2006 and is operated at 200 Hz sample frequency and is interfaced to the ship's high-speed fibre-optic network in order to provide data to the crew.

For the hybrid prototype system, a total of 20 *Narada* wireless units were installed throughout the ship and interfaced to single or tri-axial accelerometers and foil strain gauges; a total of 28 sensor channels (8 strain, 20 acceleration) were added. These are sampled at high rates of 100 to 1000 Hz to capture slamming events and the wireless monitoring system had to be divided into three separate networks to avoid wireless bandwidth issues. The *Narada* units provide short-range communication of data within the ship compartments from the sensors to wireless receivers connected to the ship's fibre-optic network.

Side-by-side comparisons of responses measured by the SPDAS and the wireless system demonstrated that the wireless sensors were generally accurate and that there were only relatively small amounts of data loss due to wireless communication. These losses were attributed to a number of causes such as communication distance, multi-path transmissions, reflections and line of sight obstruction and it was noted that “wireless sensors located near their receivers or those that used directional antennas performed extremely well in the sea trials”. The use of the wireless units had avoided the cost and effort required to install a wired system [29].

Although only installed as a prototype to demonstrate the efficacy of the wireless system, the SEA FIGHTER trial demonstrates that there are merits in this approach and there may be potential application of this technology in installation on navy ships, particularly existing ships where the installation of additional cables is difficult and costly. The SEA FIGHTER trial of the *Narada* system was carried out over a period of two months including both at-sea and in-harbour and therefore long term reliability in a naval environment is yet to be established. The long term effects of heat, humidity and vibration and suitable methods of protection against physical damage (without reducing wireless communication distances) all need to be investigated.

#### 5.3.4 RV TRITON

The installation of a network of fibre-optic sensors for structural monitoring of the UK Research Vessel (RV) TRITON during rough weather sea trials was reported by Kiddy et al [30]. This was part of the TRITON research and development program and was a collaborative effort between the UK Defence Science and Technology Laboratory (Dstl) and the US Naval Surface Warfare Center, Carderock Division (NSWCCD). The development and installation of the monitoring system was carried out by Systems Planning and Analysis, Inc. under sponsorship from the United States Navy, Office of Naval Research (ONR). The system included 35 temperature compensated fibre-optic strain sensors on three separate fibres for measurement of primary loads, and a further 16 compensated sensors on a single fibre for measurement of secondary (slamming) loads, the latter sampled at 1600 Hz and the other three fibres at 100 Hz. The instrumentation system also recorded navigational information, environmental data (wind velocity, wave height and direction, temperature, etc), machinery parameters, and data from more than 200 local strain measurements using resistance strain gages.

Important observations and conclusions reported by Kiddy et al [30] included:

- i. Reduced cabling compared to traditional electronic gauges and shielded electrical cables. This helped to reduce overall system weight, installation and troubleshooting time.
- ii. Detailed planning for such installations is vital, particularly when installation is remote from the laboratory.
- iii. The preferred way to work with optical fibre sensors is to know in advance precisely where they are going to be installed so that sensors can be fabricated and prepared in a friendly environment.
- iv. It is far easier to coil up extra fibre than it is to splice additional segments together just to reach a “few extra feet”.

- v. Always practice an installation prior to doing the actual installation.
- vi. It can be extremely difficult to replace the failed sensor if there are multiple sensors on a single fibre.
- vii. The program demonstrated the “utility, convenience, and performance of Bragg grating fibre-optic strain gages for large-scale monitoring programs”.

#### 5.3.5 Acoustic emission monitoring

Acoustic emissions are short bursts of elastic energy released during plastic deformations of metals and provide a means of crack detection and monitoring of fatigue damage in structures [31]. The technique has been used for a number of years for monitoring of offshore structures but does not yet have widespread application in the shipping industry, although some trials onboard ships have been reported in recent years, including:

- i. A concept feasibility and development study involving a single hull tanker, a double hull tanker and new class of naval vessel was carried out by Lloyd’s Register under a Joint Industry Program (JIP) [31].
- ii. A joint development project between Alaska Tanker Company, American Bureau of Shipping and MISTRAS Group Inc to trial acoustic emissions technology for detection of cracking on a 125,000 DWT tanker the PRINCE WILLIAM SOUND [32], and

Although these and other experiences have demonstrated the feasibility of fatigue crack detection in ship structures through acoustic emissions, one of the main drawbacks is the number of sensors and amount of cabling required to allow significant coverage of the hull. Harper [33] suggests that future developments may make it possible to integrate large numbers of transducers into a single optical fibre, which would largely overcome this problem. It would then be cheaper and easier to apply than the present piezoelectric transducers, but this seems to be some way off. A further drawback as far as global hull monitoring is concerned is that the application of acoustic emissions is limited to the detection of cracks and it provides no indication of strain levels and is not able to infer loads or structural responses at other locations.

Notwithstanding the complex nature of acoustic emissions crack detection systems, Snell [10] noted that an advantage of acoustic crack monitoring over the strain gauges is that acoustic emissions systems can indicate when a crack is present and when it is growing, whereas strain gauges can only help to predict these events. Trials on HMS DAUNTLESS have indicated that strain gauges may be used to help interpret acoustic emissions sensor results so that the development and growth of cracks may be related to particular types of loading events and so lead to better management and treatment of defects. The use of ‘targeted’ acoustic emissions systems that limit the extent of cabling and sensors by the use of localised signal processing, possibly wireless data transmission and restricting monitoring to only potential fatigue ‘hot spots’ areas was suggested as a viable approach for future ships [10].

## 6. HSMS Technologies

As noted earlier, a feature of HSMS development over the years has been the changes in the sensor and data transmission technologies and these have an effect on their suitability for navy ships.

### 6.1 Strain Gauges

Strain gauges are the primary sensor utilised by HSMS and these are broadly separated in long base strain gauges (LBSGs) and short base strain gauges (SBSGs).

#### 6.1.1 Long Base Strain Gauges

As their name suggests LBSGs are long gauge length strain measurement sensors, typically around two meters long but may be shorter, down to 500 mm if required. These provide unidirectional strain measurement using a Linear Variable Differential Transformer (LVDT), Linear Displacement Transducer (LDT) or a fibre-optic sensor. The latter was under development at the time of the Ship Structure Committee report [18], but can now be considered as proven in service with a number of the COTS systems listed in Table 1 having an option for fibre-optic gauges.

By virtue of their length, LBSGs are relatively insensitive to local stress concentrations as they measure the changes in displacement between the two ends of the sensor, effectively 'averaging out' high localised strains. LBSGs require a clear flat area for installation and due to their size are generally suitable only for weather deck applications on large ships such as tankers and bulk carriers where space is more readily available (Figure 6).

As is pointed out by Forestier and Austin [4], LBSGs measure strain in only one direction and shear strains are not measured and must be assessed by the loading computer. Ships that have large deck openings are subject to significant torsional shear strains, which add to the vertical shear strains. The limited number of LBSGs therefore gives only a partial view of the strains of the structure that is true "...only under the following conditions:

- the structure is undamaged,
- the static loading is known:
  - the estimation of the actual static loading is true,
  - the cargo is in a normal position,
  - no compartment is flooded,
- actual waves satisfy the hypotheses used in the structural computations (no exceptional waves)."



Figure 6. HULLMOS® LBSG Installation(Source [4])

#### 6.1.2 Short Base Strain Gauges

SBSGs are considerably more compact than LBSGs and four different sensor technologies in use with the systems in Table 1 have been identified: conventional bondable or weldable<sup>††</sup> foil gauges, fibre-optic sensors, strain rings and short length LVDT type sensors. The shorter gauge length of SBSGs means that there is much more flexibility as to where the gauges can be located and so they are generally more suitable for Navy ships which have much more complex structures and have less clear deck areas than tankers and bulk carriers. The placement of these gauges is however sensitive to localised stress concentrations so care must be taken as to where gauges are placed and how the results are interpreted; tri-axial rosettes are usually required to correctly identify stresses in areas where stress concentrations occur.

Examples of some of the different SBSGs used in HSMS listed in Table 1 are shown in Figure 7. These have overall lengths varying between 150 mm to 375 mm (excluding attached cables) and so may be installed in virtually any part of the ship with the general exception of oil and chemical tanks. Gauges are usually bonded directly to the structure or mounted to a base and housed within a sealed enclosure for protection from fluids and physical damage; the base is then stud bolted to the ship structure. Additional protection

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<sup>††</sup> These are standard foil gauges that are pre-bonded to a metal (stainless steel) shim and are fixed to the ship by way of hundreds of small (0.5 mm) spot weld welds [34].

of directly bonded gauges may be provided through the use of fibre reinforced epoxy coatings.






|   |  |
|---|--|
|    |  <div data-bbox="900 546 1315 703">  <p><b>Fiber optic short-base sensor</b><br/> <b>Maker:</b> Light Structures AS<br/> <b>Approvals/testing:</b> DNV type approval</p> </div> |
| (a) Typical weldable foil strain gauge [35]   | (b) Light Structures SENSFIB fibre-optic SBSG [36]   |
|  <p>Length 100mm</p> <p><b>SBSG</b></p> |   |
| (c) Rouvari Oy HULLMOS <sup>®</sup> SBSG [37]   | (d) Straininstall Strain ring [38]   |

Figure 7. Examples of SBSGs used in COTS HSMS.

Email contact was made with a number of these vendors listed in Table 1 to seek further information regarding their systems, and there are some relevant comments in the application of SBSGs to be noted:

- i. Bonded or weldable foil gauges (Figure 7(a)) are typically only used for temporary installations and (short term) dynamic applications. BMT Scimar suggested that the life expectancy of foil gauges in wet locations is measured in terms of weeks or (at best) months [34].
- ii. Light Structure advised that their SENSFIB fibre-optic SBSGs (Figure 7(b)) can be installed in cargo and bunker tanks and recommend these sensors generally in preference to LBSGs. The SENSFIB fibre-optic sensor is fully sealed together with its cable and it is claimed to be suitable for inside tanks. It may be provided with virtually any desired length of cable (with up to 200 m standard) so that cable joins can be minimised. A triaxial ( $0^\circ$  -  $45^\circ$  -  $90^\circ$ ) sensor for use in applications with non-uniform stress fields [36] is available.
- iii. The HULLMOS<sup>®</sup> SBSGs (Figure 7(c)) utilise either a conventional foil or fibre-optic sensor sealed inside a protective casing but are not suitable for oil or chemical tank installations [37].

- iv. The StrainAlert system uses either a 'strain ring' (Figure 7(d)) or LVDT type sensors in their SBSGs, with one version being encased in a steel chamber allowing for continued immersion down to 100 m [38].

### 6.1.3 Strain Gauge Temperature Compensation

All strain gauges are sensitive to changes in both applied strain and changes in temperature. The raw sensor outputs include the effects of both and compensation for the temperature effects is required to ensure accurate conversion of strain to stress. There are a number of temperature influences that should be compensated for:

- i. Expansion or contraction of the structure (due to its coefficients of thermal expansion) results in strain measurement but no actual stresses (see 2.6).
- ii. Differences between the coefficients of thermal expansion of the ship's structure and some gauges such as LVDTs,
- iii. Changes in the resistance of foil gauges and cabling with temperature,
- iv. Changes to the 'Bragg wavelength' (the basis of strain measurement employed by fibre-optic sensors) brought about by temperature changes.

Likewise there are a number of different methods employed for temperature compensation and these vary depending on the type of gauge, although typically the use of a co-located temperature gauge is required. Methods that may be used include:

- i. **Foil resistance gauges.** A 'dummy' strain gauge is attached to a tab or block of the same material as the hull, and subject to the same temperatures but not subjected to physical strain. Alternatively, in cases of uniaxial strain, the dummy gauge is attached perpendicularly to the active gauge. The dummy gauge is connected in a Wheatstone bridge circuit with the active gauge so that the temperature induced strain in the dummy gauge is subtracted from the apparent strain of the active gauge [39].
- ii. **Fibre-Optic Sensors.** Strain sensors are usually accompanied by an adjacent temperature sensing fibre-optic sensor. This second sensor may be encased in a small tube so that it does not experience mechanical strain. The tube is usually made from polyimide and is bonded to the structure, similar to that shown in Figure 8(a) [40]. An alternative approach (developed by Systems Planning and Analysis, Inc., see Kiddy et al [30]) called a 'dual-parameter flat-pack' (Figure 8(b)) integrates both strain and temperature compensating sensor on the same optic fibre in a polyimide substrate. The temperature compensation sensor is loosely shaped into a curve within the package so that it does not sense mechanical strain along the sensor axis. In both cases the response of the temperature compensating sensor is subtracted from the active strain gauge response to enable both the structural strain and the temperature to be determined.
- iii. **LVDT LBSGs.** The sensor core is usually a different material to the hull structure to which the gauge is attached and is free to thermally expand and contract independently of the hull structure. The different coefficient of thermal expansion results in voltage outputs that if uncorrected is interpreted as strain. The core rod is typically made of stainless steel with a coefficient of around  $17 \times 10^{-6}$  m/m °C



whereas ordinary steel has a value of around  $13 \times 10^{-6} \text{ m/m } ^\circ\text{C}^{\S\S}$ . Inbuilt signal processing is required to compensate for the different rates of thermal expansion and regular calibration of these gauges is needed to ensure consistency.

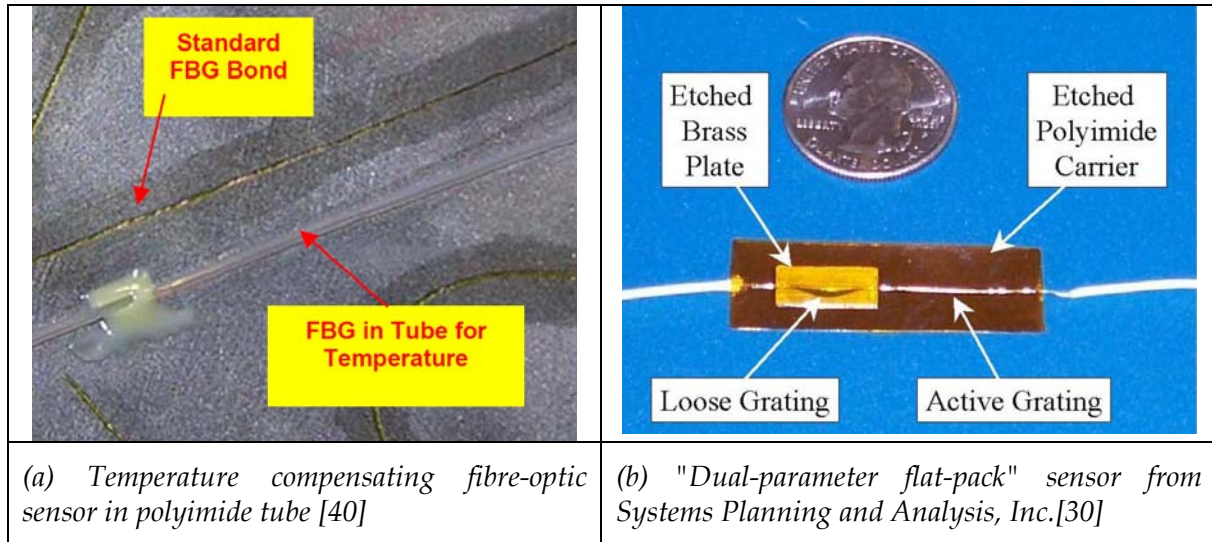


Figure 8. Examples of different methods of temperature compensation of fibre-optic strain sensors.

It is noted in NATO publication AG-160 [40] that "temperature sensitivity is a non-trivial problem" and that although "methods developed for conventional strain gauges are by now well established and tractable, the temperature sensitivity issue nevertheless represents an added complexity that must be dealt with to ensure that accurate strain data are acquired"\*\*\*. This comment applies equally to fibre-optic strain gauges and a thorough treatment of temperature compensation issues is necessary when selecting and installing HSMS.

## 6.2 Slam Monitoring

A key benefit of hull monitoring systems has been to warn of slamming events to allow corrective action to be taken, which in turn reduces fatigue damage accumulation. Slamming may be detected through different means:

- i. Pressure sensors in the bow to warn of slamming when a zero pressure reading occurs as a result of bow emergence†††.
- ii. Vertical accelerometers in the bow and stern that are used to infer the occurrence of slamming through estimation of the impact of the water on the forefoot of the

§§ Values cited in the literature vary slightly and these are typical rather than directly referenced values.

\*\*\* For example, the project outline for the Ship Structure Committee program [17] identified that strain gauges should be temperature compensated.

††† Slamming pressure may also be measured directly but a single sensor is of limited value as pressure at a point is an unreliable indicator of the actual slamming load. A number of transducers and hull penetrations are needed as well as high response and sampling rates so that the pressure field may be mapped.



- vessel. This is supplemented by information from the inertial navigation system or separate motions sensors located near the centre of gravity of the ship to help determine sea conditions, or
- iii. Through strain monitoring of bow panels that are directly affected by slamming so that mean pressure across the panel can be inferred.

More recently outputs from multiple accelerometers have been used to detect slamming through existence of vibratory bow acceleration in the two-node mode vibration frequency of the hull girder, the amplitude of which declines with time (Forestier and Austin [4]). The placement of accelerometers as close as possible to the extreme ends of the ship is particularly important for this system so as to maximise the two-node vibration detection. Accelerometers use 'off the shelf' sensor technology (including fibre optic) and are hard-mounted to the structure. Little information on specific pressure gauges has been located in development of this report, although it is noted that they are expensive to install and are becoming redundant as multiple accelerometer systems are developed [4].

### 6.3 Data Communication

As noted in the preceding paragraphs, strain gauges may employ either LVDT, LDT or fibre-optic sensors; fibre-optic being the newest technology. There are a number of benefits with fibre-optic systems that are relevant to navy applications (e.g. see [20] and [40]):

- i. Sensors and data transmission are immune from and do not generate electromagnetic interference,
- ii. The systems are inherently 'intrinsically safe', enabling them to be located within explosive environments without the need for Zener barriers [13],
- iii. They are relatively lightweight and have lower power consumption compared to traditional copper wire technology,
- iv. It is possible to include multiple sensors on the one cable through wavelength multiplexing and multi-fibre cables in order to reduce installation costs. This may not be recommended for all applications as cable damage will disable all sensors on that cable.
- v. Reduced noise levels in signals compared to conventional strain gage techniques which improve the accuracy of information outputs.

One of the drawbacks to fibre-optic systems is that special techniques are required to install them particularly in regards to connection, but this can be reduced by having custom length cabling provided (Section 6.1.2) so cable joins are minimised. Cable run lengths then need to be determined reasonably accurately.

Wireless data transmission is also a recent development for HSMS. Swartz et al [29] report on a prototype hybrid (wireless / fibre optic) system installed on the high speed littoral combat vessel FSF-1 SEA FIGHTER, an aluminium catamaran and it is cited as an option for the HMS Hull Monitoring System (Appendix A). As discussed in Section 5.3.3 this is not as yet considered a proven technology for navy application as the long term reliability of the wireless data acquisition and control units in this environment has not been established.

## 6.4 Data Processing and Management

On-board processing of data and management are the core of HSMS. Data processing is typically based around personal computer (PC) systems and COTS systems are generally designed to interface to a ship's management and navigation systems as well as sensors such as wind speed anemometers. Most COTS systems in the past have operated in a Windows environment (see Slaughter et al [18]) but there now appears to be a trend towards Linux operating systems, as for example with both the SENSFIB and HULLMOS<sup>®</sup> systems. It is noted by Slaughter et al [18] that "manufacturers prefer dedicated PC's to maintain configuration control over the HSMS. The cost of a single service call to reconfigure a sailor-modified system will generally be more than the cost of another PC". Class approval of COTS HSMS therefore includes the hardware and software to ensure configuration control is maintained.

In order to provide decision support information and alarms, real-time data processing is essential, as is the periodic storage of measured data and processed information. The volume of raw data will be very large, and once on-board measurements have been used to validate numerical modelling it may be preferable to store only processed data, such as minimum, maximum and mean values, standard deviations, cumulative rain flow counting and so forth. Capturing of time history records for short periods surrounding events that exceed predetermined threshold levels may also be warranted.

## 6.5 Human-System Interface

The HSI for HSMS is primarily through the GUI and an example of a screen display for the HMS Hull Monitoring System is shown at Figure 9. This example demonstrates some typical information that may be displayed and it can be seen that there are a number of other screens available via tabs at the bottom of the screen.

As the role of navy ships is very different to that of commercial ships the specification of display requirements for navy applications will need special consideration. Displays also need to allow for different levels of monitoring on different ships as some may have base-level monitoring whilst others may be far more comprehensive and provide operator guidance for boat and helicopter operations. To reduce training and provide ease of use across navy fleets where crews may change regularly and individuals may be posted to a number of different ships, it is preferable to have a common HSI across the fleet.

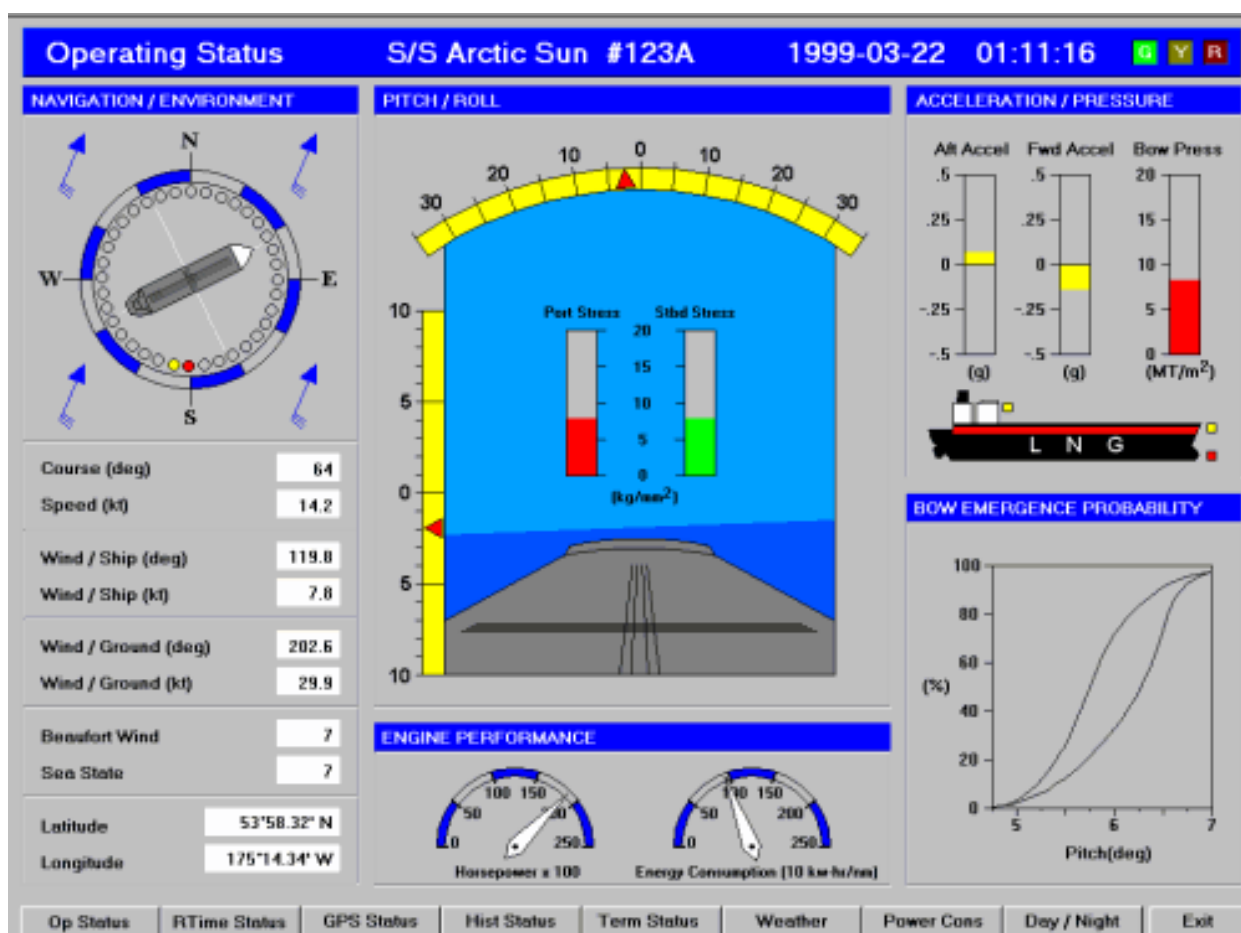


Figure 9. Screen page display from the HMS Hull Monitoring System (MCA Consultants, Appendix A)

Navy applications will also typically require multiple displays throughout the ship, for example on the bridge, in the operations and machinery control rooms and at boat and aviation control stations. Incorporation of the HSMS into the ship's control and management system would avoid the need for additional cable installation and stand-alone displays, although it may cause some issues with Classification Society requirements if they are involved. Development of the data displays should involve relevant operators, engineers and original equipment manufacturers to ensure that the data processing undertaken by the system and the information displayed fully meets the need of the users and operators.

## 7. HSMS for Navy Ships

Navy ships come in a large variety of sizes and configurations and their roles are very different to that of large commercial ships. The key benefits to be gained from the use of HSMS on navy ships are somewhat similar to those on merchant ships.

## 7.1 Key Benefits

There are significant benefits to be gained from the installation of HSMS on merchant ships and those typically cited include:

- i. The provision of on-board guidance and alarms to enable the crew to act to avoid overstressing of the hull,
- ii. Through life cost savings as a result of reduced fatigue damage to the hull,
- iii. Integration with navigation and weather forecasting can provide improved route planning and possible fuel savings, and
- iv. Data collection over a long period is used for the improvement of through life management practices as well as in the development of improved designs through a greater understanding of the long term extreme and fatigue loading of ships.

Navy vessels can be expected to obtain similar benefit to these but are likely to be realized to varying degrees, as now discussed.

### 7.1.1 Operational Warnings

Navy ships are operated quite differently to commercial ships and are not always able to respond in the same way to HSMS guidance and alarms, which can then as a result be seen as annoying and unwanted. Navy ships are often unable to avoid heavy weather conditions, to change course or slow down to reduce hull loading because mission imperatives may require them to be at a certain location at a certain time. Live structural monitoring will inform the ship's commander as to whether or not the ship is at short term risk of damage as well as highlighting overall trends in fatigue damage. If levels are set appropriately so that alarms are not sounded unnecessarily then the benefit in knowing the stress levels in the hull during these critical events is clearly evident.

### 7.1.2 Through Life Costs

The broad range of tasking of navy ships means that the operational profile of these ships is likely to vary over the life of the ship and across the fleet. Accumulation and analysis of HSMS data across a class of ships enables the different operating profiles of individual ships to be established. This will highlight usage differences and provide a basis for improved maintenance practices. Combined with information relating to 'hot spot' stress areas, the long term loading statistics allows targeted inspections of critical areas on the basis of likely fatigue damage risk in these areas. This can lead to through-life cost savings by avoiding unnecessary inspections of low risk areas and earlier detection of defects in high risk areas through additional targeted monitoring of these areas.

### 7.1.3 Integration with Other Systems

A potentially significant advantage from the integration of HSMS with other systems is the improved safety and operability of off-board systems such as boats and helicopters. Monitoring of ship motions and wave environment and integration of other information already available on the ship, such as ship speed and heading, wind speed and direction is already quite common in HSMS. Incorporation of predicted motions responses (from seakeeping analysis) and the safe to operate limits for launch and recovery of off-board

systems, enables the best speed and course to be determined so as to reduce ship motions and maximise operating envelopes. With the development of a wide array of deployable, unmanned vehicles suitable for navy applications now available, the integration of HSMS with these other systems and information is seen as potentially very beneficial.

#### 7.1.4 Improved Designs

As previously mentioned, some of the earliest hull monitoring was carried out on navy ships. The primary focus of these was to gain a greater understanding of the wave bending loads responsible for the primary (hull girder) extreme and fatigue loading of warships (e.g. [19]). Navies often lead the development of ship structural design (e.g. aluminium superstructures and trimaran ships) and more recently navy ships have been monitored to investigate stresses at critical locations in novel hull forms, such as the cross deck structure of multihulls, (e.g. [20], [29] and [30]). Installation of HSMS on ships during build enables a full stress history of the vessel to be compiled so that this may be used to provide a better understanding of the loads to which ships are exposed and to help identify causes of unexpected fatigue problems should they occur. The development of a new HSMS, particularly if this includes the adoption of new technology, is expensive and requires a great deal of development and analysis effort. The trend towards the adaptation of commercial systems for military applications, as seen in Section 5.2, can be expected to continue.

## 7.2 System Configuration

The configuration of HSMS on navy ships is generally likely to be more complex than the typical installation on bulk carriers and tankers (Figure 2) as seen in the MOTS and developmental systems discussed above. Additionally there are more constraints on system installation and typically greater level of analysis is required, as discussed below.

### 7.2.1 Monitoring Parameters

The level of complexity of HSMS is dependent on the parameters to be monitored and these can vary from the most basic installation such as the USCG WHECs (Section 5.2.3) through to very complex systems such as on SEA FIGHTER (Section 5.3.3). Table 2 provides a very broad overview of the parameters typically monitored, the types of sensors that this may involve, an indication of the type of additional information that is needed for each type of monitoring parameter and the potential outcomes that this may provide. This is by no means an exhaustive assessment and it is provided as an indication of these relationships only. Whilst parameters may be able to be monitored separately to provide specific outcomes, it is generally to be expected for HSMS that on-board processing and monitoring of all the previously listed parameters is also carried out.

### 7.2.2 Installation

There are greater constraints imposed on the location of sensors on warships, even the larger ones, due the space and weight limitations and the potential interference they will create with on-board activities. All warships will have some restrictions as to where sensors such as strain gauges may be able to be placed on their weather decks, particularly the midships waist, as these areas are needed for frequent movement of equipment, stores

and personnel. Flight deck clearance requirements and positions of the replenishment-at-sea points may preclude the installation of larger sensors in these areas altogether.

### 7.2.3 Hull Girder Monitoring

It is essential for a HSMS to be effective, that the results from monitoring stresses at one location be able to be related to the structural response at other locations. Base COTS system configurations have been developed for large, wall-sided ships that are effectively prismatic beams and for which the assumption of simple beam theory involves relative small error. The complex structures found in frigates, destroyers and multihulls somewhat invalidate this assumption and generally a larger number and type of sensors is needed for reliable evaluation of the loads. The placement of strain gauges should be supported with seakeeping and FEA to ensure that they are not unduly influenced by 'hot spots' or shadow zones. Monitoring of the more critical locations (e.g. superstructure corners) is important for validation of FEA calculations.

As discussed in Section 3.1, warships are more lightly framed than merchant ships and may be more prone to local buckling. This buckling is induced by hull girder bending loads but initialisation is generally a localised phenomenon. Buckling also occurs under compressive loading and so is most likely to occur in the upper, forward part of the ship where the influence of slamming is most evident. The use of ultimate strength analysis to determine the relevant buckling limit states is needed to identify high-risk locations and to establish appropriate safe bending moment levels for alarms. Buckling results in rapid load shedding and so the use of keel gauges is recommended to ensure that bending moments are reliably determined.

Table 2. Overview of the increased level of system complexity associated with monitoring of additional parameters (In general it is expected that with each category of 'Monitoring Parameter' the sensors, on-board processing and monitoring of all the previously listed parameters is present.)

| Monitoring Parameter  | Sensors  | Supporting Information   | Potential Outcomes  |
|---|--|--|---|
| Cargo loading<br>Hull Girder Vertical Bending<br>Hull Girder Lateral Bending<br>Hull Girder Torsion | Main deck LBSGs or SBSGs, port & starboard                         | Section properties<br>Operational profile<br>Structural analysis<br>Post-voyage analysis | Overload alarms<br>Hull girder load history<br>Hull girder fatigue indicator  |
|   | Bilge keel strain gauges   | Limit state analysis (FEA)   | Improved overload alarm (buckling risk)<br>Improved hull girder fatigue   |
| Temperature   | Thermocouple or fibre-optic temperature sensor                     | Thermal coefficients   | Temperature compensation<br>Thermal history   |
| Slamming<br>Green Seas over Bow<br>Whipping   | Accelerometers, pressure transducer<br>High speed data acquisition |  | Slam avoidance warning<br>Slam event history<br>Improved hull girder fatigue indicator  |
| Hot-spot stress<br>Cross deck structures stress Side<br>Frame loads<br>Hatch Corners stress         | Local strain gauges (SBSG)   | Structural analysis (FEA)  | Local stress/overload monitoring<br>Detailed structural load history (e.g. multihull spreading loads)<br>Detailed fatigue indicator |
| Wet deck slamming (multihull)   | Local accelerometers and strain gauges (SBSG)                      |  | Wet deck slam warning<br>Wet deck slam event history<br>Improved fatigue indicator  |
| Navigation data   | Ship systems   | Sea keeping analysis<br>Weather forecasts  | Weather Routing<br>Economic Routing   |
| Wave Environment  | Wave radar<br>Motions sensors                                      | Launch and recovery safe to operate limits   | Operator Guidance for Off-board systems<br>Improved routing<br>Improved load/fatigue assessment                                     |

#### 7.2.4 On-Board Fatigue Prediction

On-board prediction of fatigue damage by COTS HSMS is based on the concept of hull girder fatigue life as outlined in Section 3.2.1. Hull stress monitoring only directly measures stresses at the actual strain gauge locations and these may not necessarily be the areas at greatest risk of fatigue failure. Cracking will more likely occur at structural 'hot spots' (local structural details where stress concentrations occur) and the use of FEA is needed to infer stresses at these locations based on those monitored by strain gauges. The complex nature of navy ship structures makes this a very difficult task and requires the use of both sea keeping analysis and FEA. The use of on-board monitoring of ship motions and the wave environment enables 'hot spot' stresses to be determined more directly and with greater accuracy and therefore provides a valuable addition to HSMS.

Fatigue life predictions are also based on an assumed loading profile that can only be verified in the long-term loading through-hull monitoring. This means that ships that have already been in service for a long time prior to HSMS installation will have greater uncertainty in their loading history (as well as the material condition of the hull) and so fatigue estimates are less reliable. It is therefore debatable if there is much to be gained from installing HSMS with fatigue rate assessment on ships that have only a couple of years of service remaining. In such cases, hull overloading warning based on section modulus properties<sup>†††</sup> is realistically the only monitoring benefit. In order to obtain significant benefits related to fatigue life management, monitoring needs to be introduced as early as possible, and ideally before the ship enters service.

## 8. Conclusions

Following an earlier DSTO investigation into the use of HSMS and their application to fatigue life evaluation of RAN ships, this report provides details of key technical issues relevant to these systems and discusses their application on navy ships in general.

An overview of hull structural loading and subsequent responses is provided in order to first gain an understanding of how HSMS may be of benefit. The objectives of hull structural monitoring and the typical baseline installation required by Classification Societies and found on large commercial ships such as bulk carriers and tankers is presented. These systems consist of usually four long base strain gauges for measurement of hull girder bending moments, together with accelerometers or pressures sensors for detection of bow slamming. Advice to the crew regarding loading of the hull and warnings of high stress levels is provided through a graphical user interface located on the bridge. Warnings are given when stresses exceed predetermined levels and some systems also give advice in relation to fatigue damage rates. There has been little change in this basic configuration since the International Maritime Organization originally introduced requirements in 1994.

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<sup>†††</sup> The material state of the hull must be able to be established with a reasonable level of confidence so that the load carrying capacity of the ship can be determined.



A literature and internet survey was carried out to identify the current state of the art of HSMS and information obtained fell into three categories: Commercial off the shelf (COTS), Military off the shelf (MOTS) and developmental systems. Details of a number of COTS systems were provided by vendors and are included in separate appendices for each system. Information relating to MOTS and developmental systems are reviewed and discussed within the report. MOTS installations typically have an enhanced configuration compared to the COTS system on which they are based whilst the developmental systems are one-off applications used for research. Significantly, the majority of the MOTs and developmental systems discussed utilise fibre-optic sensors and networks.

The underlying system technologies that are used in HSMS have been reviewed, particularly in relation to strain gauges, and there has been a continuous improvement from early mechanical strain gauges to fibre-optic sensors now being widespread. The latter potentially offer a number of advantages for navy HSMS as they are lightweight, high speed, not affected by electromagnetic interference and require no re-calibration once installed, although specialist expertise is required for their installation. Wireless communications, originally developed for monitoring of civil structures, have been demonstrated as a potential low cost solution for data communications but the ability of these systems to survive the harsher marine environment is not yet proven. The use of pressure sensors in the bow for monitoring of slamming is expensive and becoming redundant as distributed accelerometer systems to detect decay of whipping oscillations are developed.

The configuration and design of HSMS should include particular attention to temperature compensation of strain gauges as all strain gauges, including fibre-optic sensors, are sensitive to changes in both applied strain and temperature. The raw sensor outputs include the effects of both and compensation is needed to eliminate temperature influences that do not generate actual stresses. The methods employed are varied as they depend on the type of strain gauges and the effects that temperature change will cause. There is some question as to whether all COTS systems provide adequate temperature compensation and special consideration of the methods employed when selecting these systems is recommended.

Due to space limitations, LSBGs that are commonly used on many COTS systems are generally not suitable for installation on frigates and destroyers and may also be problematic on larger auxiliary and amphibious ships. The inherent assumption in these systems is that of an intact, prismatic hull and this means that these systems should not be used directly for more complex structures and more lightly framed navy ship applications. Additional sensors and supporting analysis are needed for these ships. The placement of strain gauges needs to be supported with seakeeping and finite element analysis to ensure that they are appropriately located and not unduly influenced by hot spots or shadow zones, and so that measured data can be properly interpreted.

Ongoing recording and analysis of data is needed for establishment of accurate loading profiles and subsequent fatigue life predictions. The reliability of fatigue assessments is improved if monitoring is introduced into newer ships and if possible installed during construction before they have entered service. For older ships nearing the end of their

service life the major benefit of structural monitoring is to provide hull overload warnings, so long as the load capacity of the hull can be reliably determined.

Navy vessels can be expected to obtain similar benefits from HSMS as those gained from installation on merchant ships (such as improved safety, reduced through life costs and greater understanding of hull loads) but these are likely to be realized to varying degrees. Monitoring of ship motions and wave environment to enhance structural loading and fatigue assessments also enables provision of operator guidance for improved routing and the launch and recover of off-board systems such as boats and helicopters development of wave environment data bases. For the RAN, the outcomes from the use of HSMS also relate directly to Life Cycle and Risk Management themes from the Rizzo Review [1] recommendations.

## 9. Acknowledgements

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## 11. List of Appendices

|            |   |          |
|------------|---|----------|
| Appendix A | HMS Hull Monitoring System, MCA Consultants   | 4 pages  |
| Appendix B | HULLFIB, Micron Optics, Inc<br>(Also marketed as STREMOS - Hull Stress Monitoring System<br>by Global Maritime Engineering, Busan, Korea) | 24 pages |
| Appendix C | HULLMOS®, Rouvari Oy / HMC / Sirehna  | 6 pages  |
| Appendix D | CPE Systems   | 3 pages  |
| Appendix E | Naviscan (HSMS), Korea Marine Technology Co., Ltd/Sea<br>Structure Technology Co. Ltd   | 15 pages |
| Appendix F | Scimar, BMT Scientific Marine   | 2 pages  |
| Appendix G | SENSFIB, Light Structures   | 11 pages |
| Appendix H | Sh.A.M.An, CETENA   | 2 pages  |
| Appendix I | SMARTSTRESS, BMT SeaTech  | 5 pages  |
| Appendix J | StressAlert, Straininstall UK Ltd.  | 4 pages  |
| Appendix K | Narada Wireless Data Acquisition and Control  | 1 page   |

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## **Appendix A HMS Hull Monitoring System, MCA Consultants**

(4 pages)

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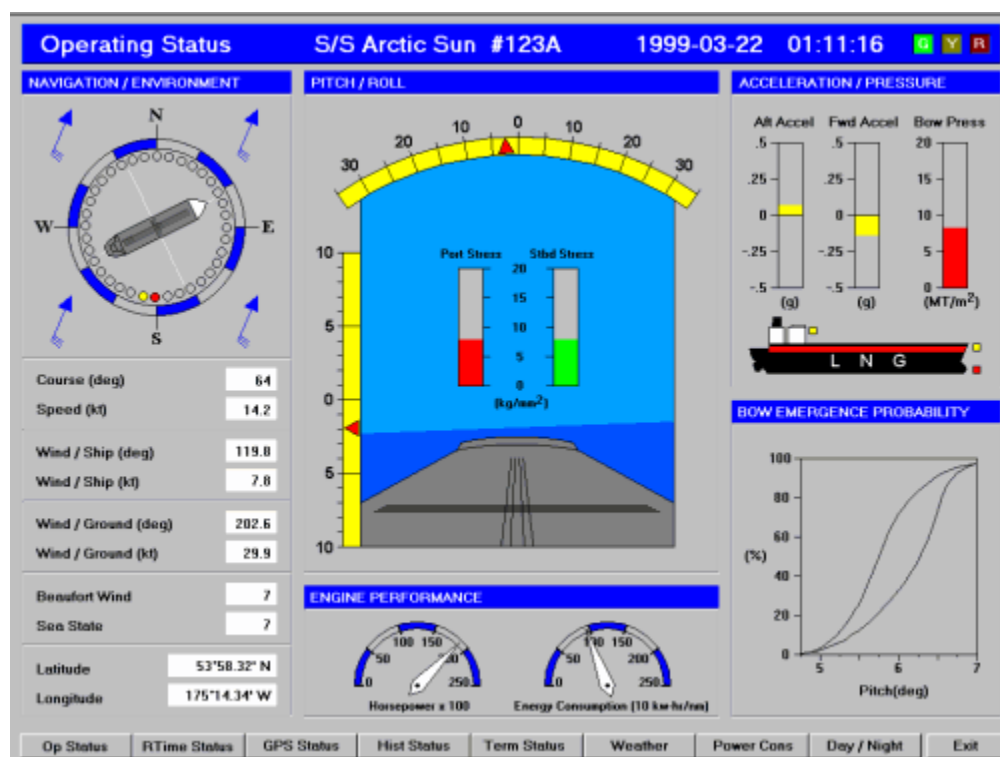
## HMS

### Hull Monitoring System

**Measure, Monitor and Avoid...Bow Emergence, Slam, and Excessive Hull Flexure With Real-Time Graphic Displays, Charts, Tables and Reports**

### Increase Vessel Operating Safety While Reducing Structural Damage

HMS is an intrinsically safe system that displays quantitative data about ship motion in intuitively clear graphic and tabular formats. At sea, deck officers navigate more efficiently, minimizing structural damage. On land, post-processing re-creates any voyage, quantifies its slams and stresses, looks for correlations, evaluates fatigue damage and helps operators plan safer routes.



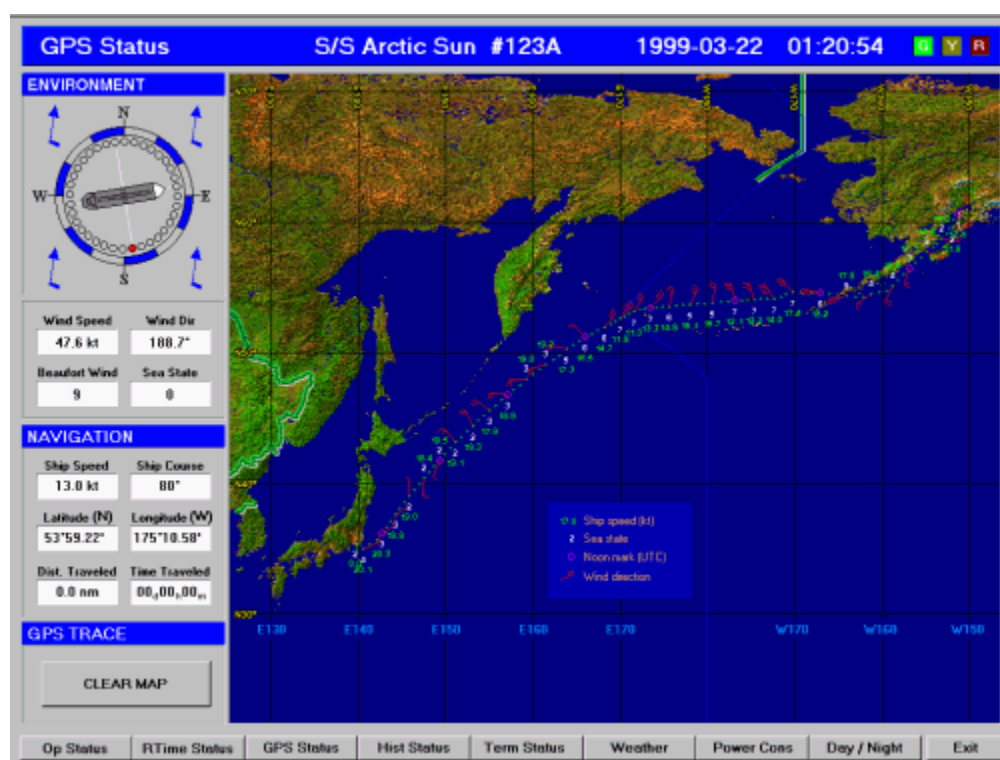
### Real-Time Displays Help Cut Structural Repair Costs

Ship owners' cost and frequency of repairs are a direct result of metal fatigue caused by hull stresses, bow slamming and vibration. HMS continuously informs wheelhouse watch personnel of deck stresses, bow pressure and accelerations. The system sounds alarms as critical limits are approached; even shows the effectiveness of the ship's latest maneuvers. Displays include:

#### Operating Status:

Animated and real-time displays for: wind and wave velocities, pitch, roll, accelerations, bow pressure, deck stress, course, speed, and slam

|                           |   |
|---------------------------|---|
|                           | probability.  |
| <b>Real-Time Status:</b>  | Continuous 60-second time-history plot for any two data channels.   |
| <b>GPS Status:</b>        | Ship's position traced against a route map with UTC noon marks.   |
| <b>Power Consumption:</b> | Displays the ship's real-time power consumption. This allows officers to see how changes in course and speed affect fuel economy.               |
| <b>Historical Status:</b> | Four-hour time-history bar chart indicating five-minute average and maximum value for: pitch, roll, deck stress, bow acceleration and pressure. |
| <b>Terminal Status:</b>   | Displays tide and current information for port. Also displays wind direction.   |



### Post-Voyage Reports Help Optimize Operating Procedures

Data analyses enhance deck officers' understanding of the ship's dynamic behavior under various loading conditions, and what to expect by season and route. Having this information allows operators to optimize at-sea procedures for safety and structural integrity by answering questions such as:

- What was the maximum roll, pitch angle etc. encountered last winter?
- Which routes are structurally critical in which seasons?
- What is the current rate of fatigue damage for various structural components?
- What is the probability of structural damage given the number of bow emergencies since the last shipyard period?

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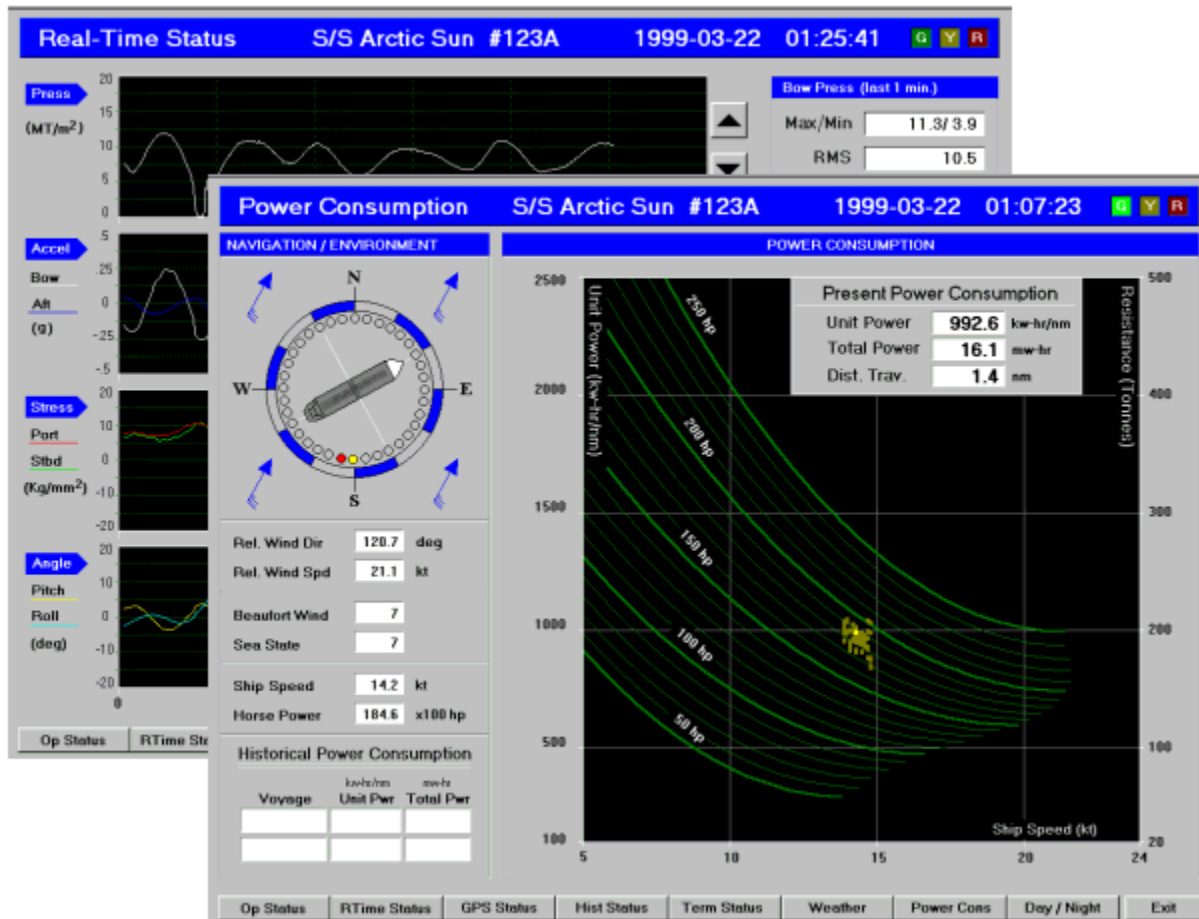
## **Appendix B HULLFIB, Micron Optics, Inc**

(Also marketed as STREMOS - Hull Stress Monitoring System by Global Maritime Engineering, Busan, Korea)

(24 pages)

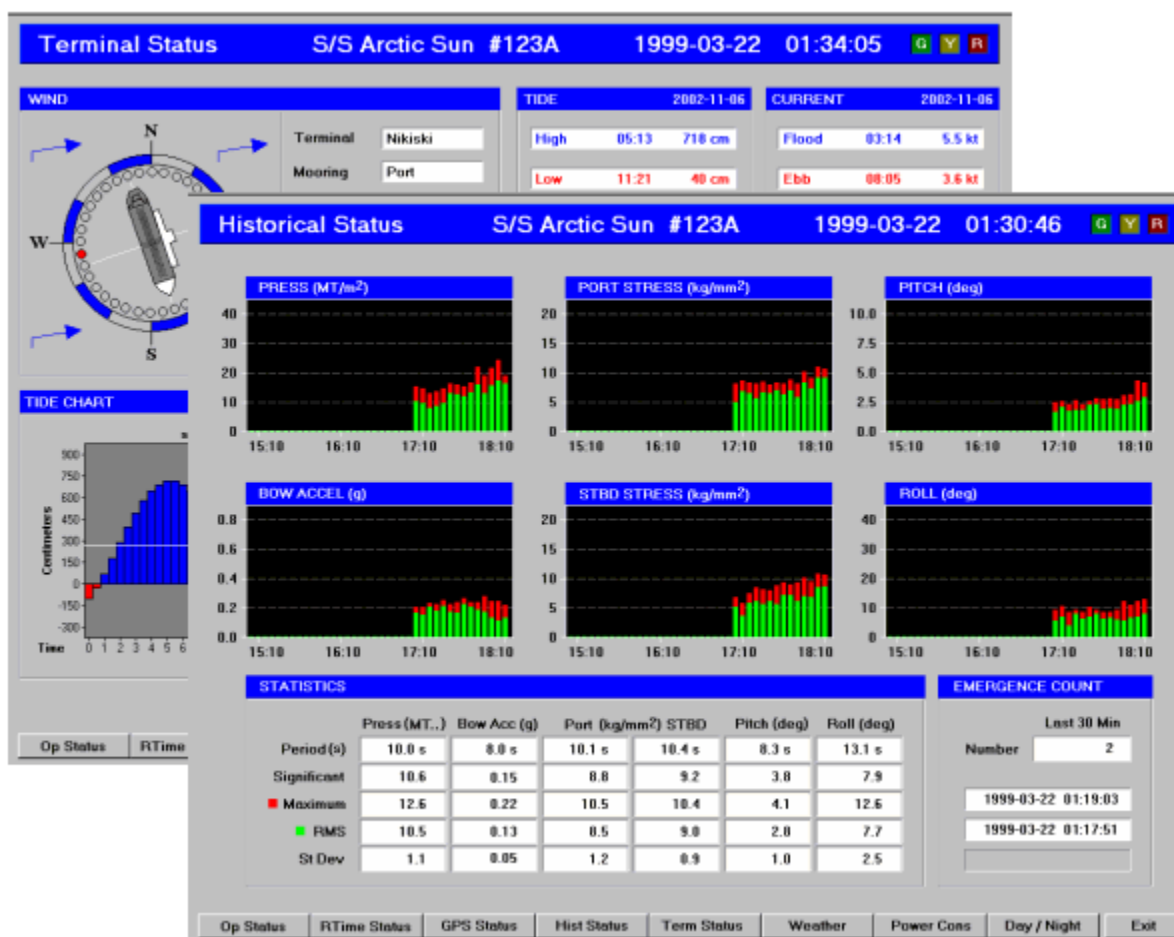
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### Flexible Component Installation

In one day, the minimum HMS configuration can be installed and activated with wireless, radio-linked data transmission to the deck-house. Alternatively, the entire system can be installed during an appropriate shipyard period.



### Standard Equipment Includes:

- Intel-based Command Center
- 16 or 32 data acquisition channels with 10Hz polling
- Bow accelerometer to measure vertical motion
- Bow bottom pressure transducer to measure emergence and slam
- Mid-deck strain gauges to measure stress
- Inclinometers to measure pitch and roll
- Utilizes ship's engine, anemometer and GPS data



### Client List:

- Marathon Oil
- Polar Tankers
- Alaska Tanker Company



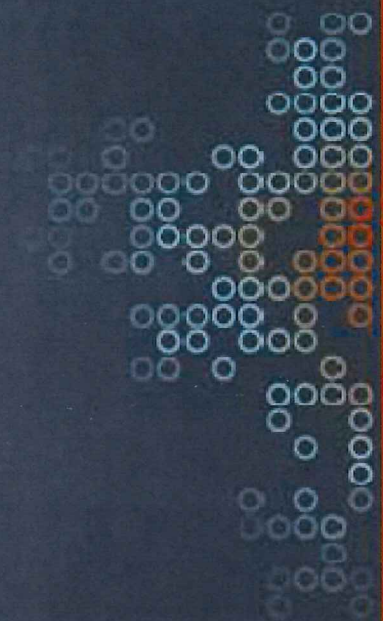


# Case Study - Transportation

## Hull Stress Monitoring System

Korea

2009



# HULLFIB – Fiber Optic Hull Stress Monitoring System

2



|                        |  |
|------------------------|--|
| Aim                    | The aim is to measure the stresses and torsions caused by waves, cargo operations and motions.   |
| Location               | Korea  |
| System Integrator      | GME, Global Maritime Engineering   |
| Customer               | Samsung Heavy Industries Co., Ltd.   |
| Date                   | March 2009   |
| Instrumentation        | <ul style="list-style-type: none"><li>• Micron Optics, sm130 Optical Sensing Interrogator</li></ul>  |
| Sensors                | <ul style="list-style-type: none"><li>• GME, 1.5m HULLFIB-LGL Strain Sensor</li><li>• GME, Fiberoptic Accelerometer and Pressure Transducer</li></ul>  |
| Software               | Customer designed  |
| FBG Technology Benefit | <ul style="list-style-type: none"><li>• No need to recalibrate sensors – zero drift.</li><li>• No electrical power at sensors – intrinsically safe.</li><li>• Sensors immune to electromagnetic radiation and no download effects.</li><li>• Long-term stability and durability.</li><li>• Built-in temperature compensation available</li></ul> |





- HULLFIB is used to monitor the behavior of hull girders during navigation, loading, and unloading. HULLFIB is also used to provide real-time information on stress levels due to longitudinal bending moment and acceleration levels due to the ship's motion.
- The system will give a warning when stress and bending moment levels and acceleration of ship motion approach levels which require corrective action such as escaping the area, reducing the speed or changing the heading of the vessel.
- In addition, the information on the navigational condition and environment is provided from the GPS, and navigation equipment etc.
- The new fiber optic technology allows any number of sensors to be fitted anywhere in the ship's hull for uninterrupted recordings of actual degree of stress.
- Major class notation of ABS, BV, DNV, LRS etc is available.



- HULLFIB-LGL long gage length strain sensor comprises two deck fixings which are either bolted or welded to the deck or the inner hull structure.
- Between them is a fiber optic sensor assembly which measures the average strain and also temperature for compensation.
- A two-way fiber optic cable exits the arrangement from one end. The complete assembly is protected by a cover for LGL or a putting compound for SGL.



1.5m HULLFIB-LGL Strain Sensor

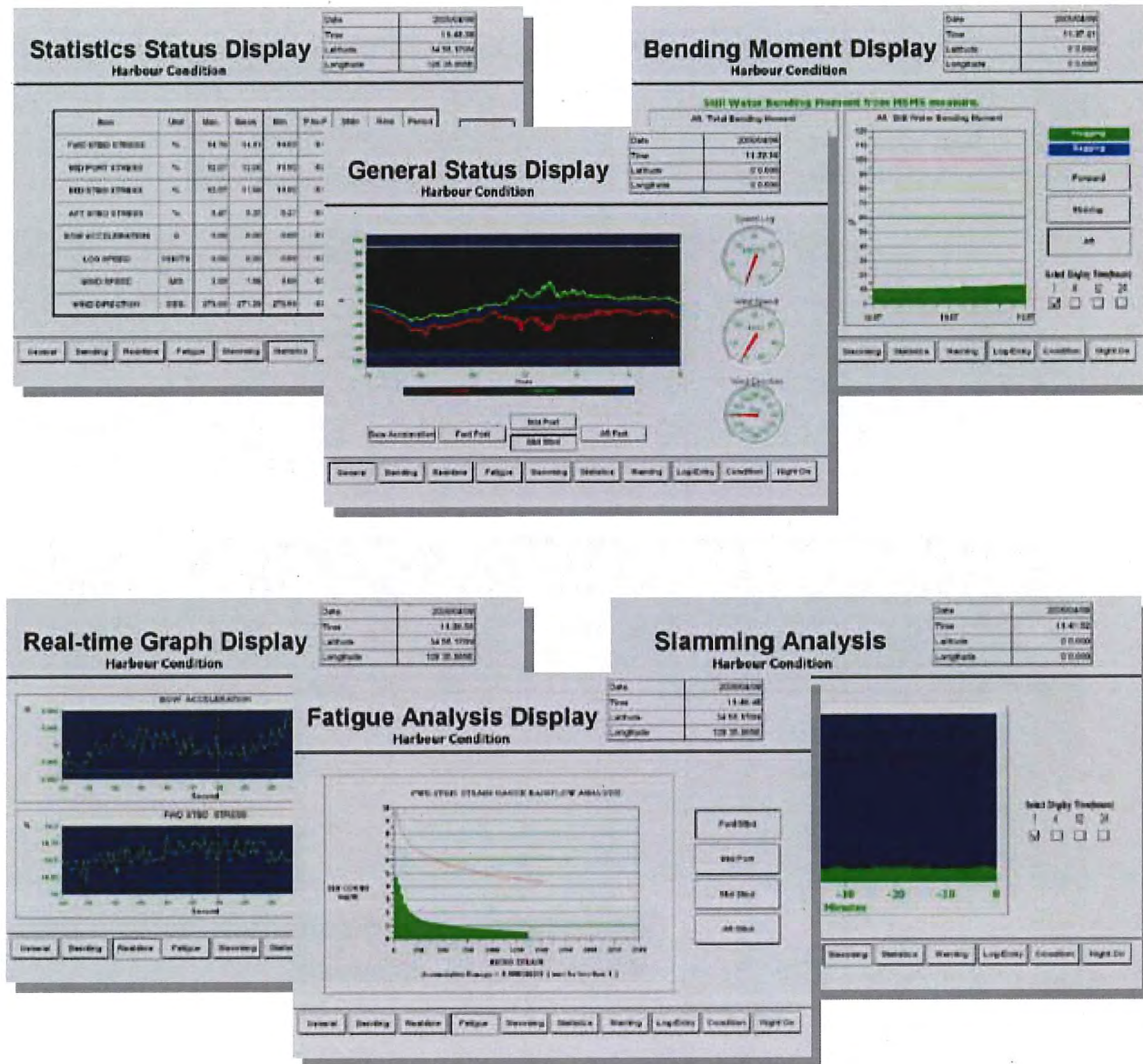


- An sm130, Optical Sensing Interrogator is used to illuminate the sensor network, read the reflected sensor wavelength and calculate the strains, temperature, acceleration, pressure, etc.
- Various interrogators are available to give the required system performance.



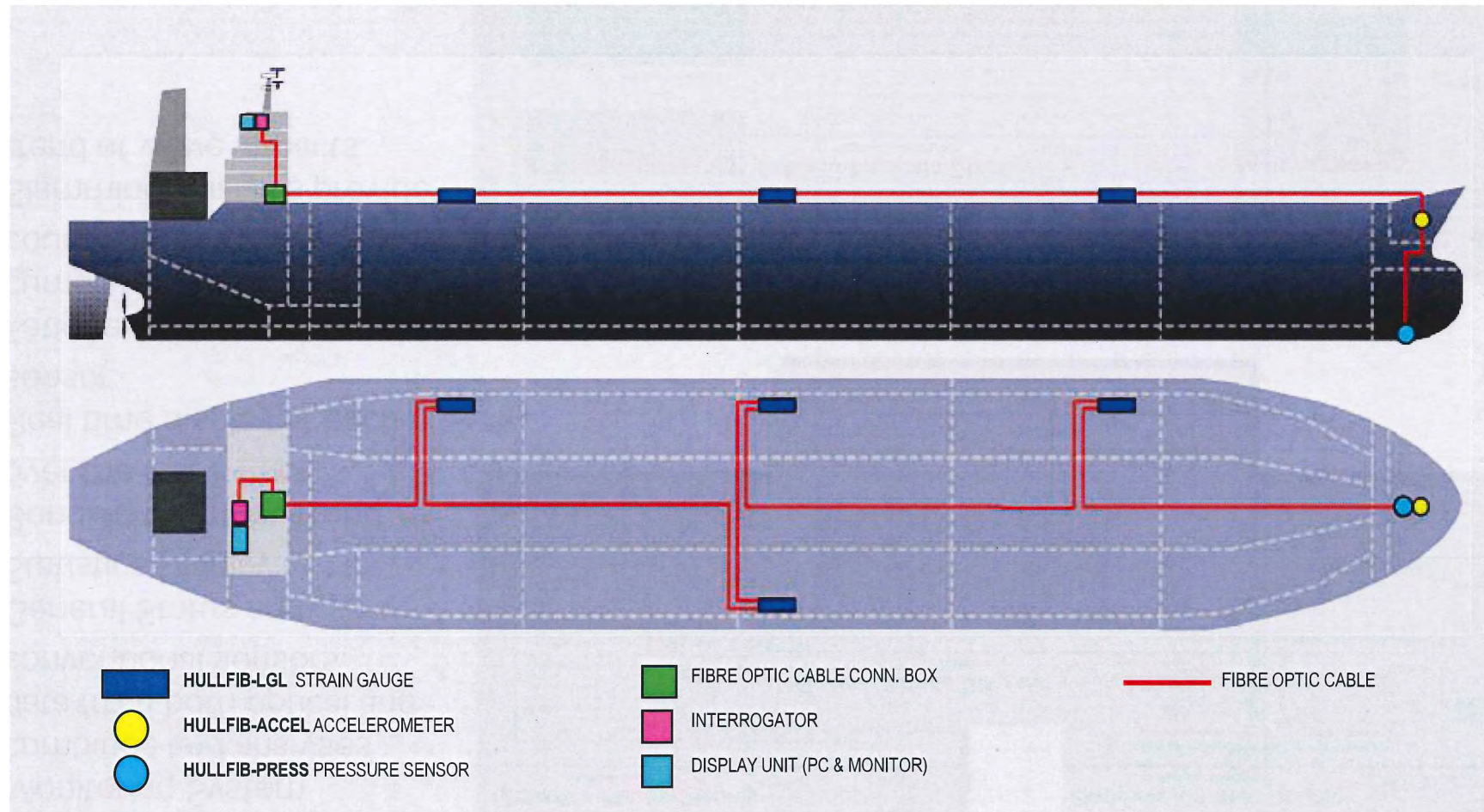
Micron Optics FBG  
Interrogation System

- Complete Software Monitoring System combines and analyses data from both optical and conventional sensors.
- General Status and Statistics Display.
- Bending Moment Trend over the last 24 hrs.
- Real time display of each sensor.
- Fatigue Analysis with cumulated stress cycle count.
- Slamming Analysis provide trend of wave impacts.





## TYPICAL ARRANGEMENT OF HULLFIB





- Results

- Vessel informed that the HULLFIB is a more convenient tool for navigation compared with conventional system adapted with electric sensors, as the annual calibration in a hazardous area is not required.
- No requirement to recalibrate sensors is a big advantage of this system.

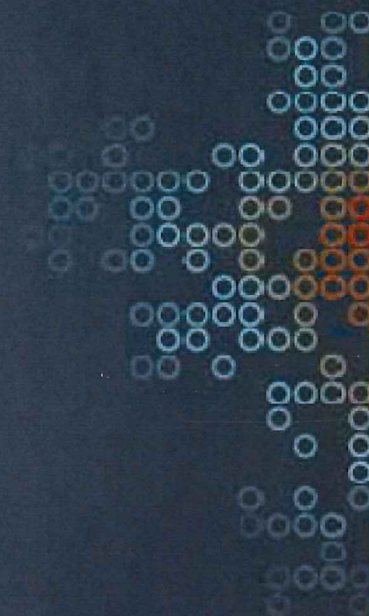
- Acknowledgements

- Samsung Heavy Industries Co., Ltd., Korea  
web: [www.shi.samsung.co.kr](http://www.shi.samsung.co.kr)
- GME, Global Maritime Engineering Co., Ltd., Korea  
Tel: +82 (0)51-265-2001, email: [gme@gmeng.com](mailto:gme@gmeng.com), web: [www.gmeng.com](http://www.gmeng.com)
- Micron Optics, Inc.  
Tel: 404-325-0005, email: [info@micronoptics.com](mailto:info@micronoptics.com), web: [www.micronoptics.com](http://www.micronoptics.com)





# Case Study: Marine Fiber Optic Damage Assessment System Mobile Bay, AL January, 2008



- HULLFIB-ACCEL and HULLFIB-PRESS are fiber optic transducers to measure acceleration and bow pressure. When required, then can be easily added to the strain sensor network and read by the same FBG interrogator.



HULLFIB-ACCEL  
Accelerometer



HULLFIB-PRESS  
Pressure Sensor



# Fiber Optic Damage Assessment System (FODAS)

2



|                        |  |
|------------------------|--|
| Aim                    | The implementation of an automated network of ship condition sensors will have a number of direct benefits that will increase ship and crew survivability during a ship damage event.  |
| Location               | System Trial on ex-USS Shadwell, Mobile Bay, AL  |
| System Integrator      | Aither Engineering, Inc.   |
| Customer               | U.S. Navy  |
| Date                   | January 2008   |
| Instrumentation        | <ul style="list-style-type: none"><li>• Micron Optics si425, Optical Sensing Interrogator</li><li>• Micron Optics sm041, Channel Multiplexer</li></ul>   |
| Sensors                | <ul style="list-style-type: none"><li>• Aither Flooding Sensors, Door Closure Sensors, and Fire/Temperature Sensors were tested</li><li>• Other Sensors available for the system: Aither FBG Accelerometers</li><li>• Micron Optics, <b>os3100</b> Optical Strain Gage Sensors</li></ul> |
| Software               | Custom Aither Software   |
| FBG Technology Benefit | Multiplexing FBG sensors monitoring different parameters.  |

- Problem Statement

- No automated monitoring system exists on Navy vessels to provide real time assessment of damage.
- Uncertainty in damage assessment can result in a ship lost during a crisis situation.

USS Cole (DDG67)



- On Oct. 12<sup>th</sup>, 2000, at 11:18 a.m. Bahrain time (3:18 a.m. EDT), when the small boat was situated on the port side of the destroyer an explosion occurred causing a 40-foot by 40-foot gash in the port side of the USS COLE. Damage control efforts to manage flooding in the ship's engineering spaces were reported successful that evening.

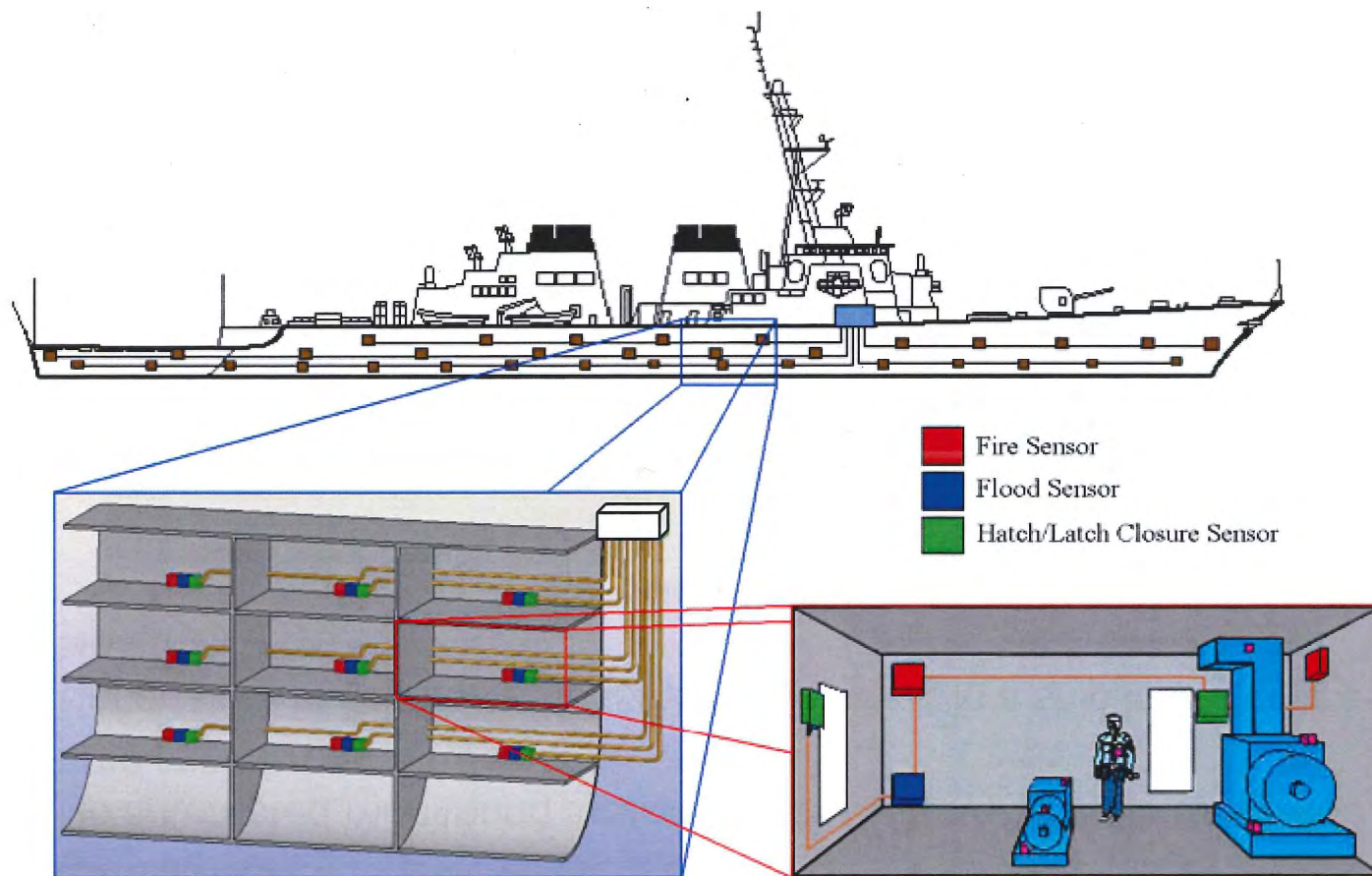


# Fiber Optic Damage Assessment System (FODAS)

4



- A suite of networked fiber optic sensors to enable real time access to superior damage assessment data.



Distributed Network of FBG Sensors

- Limited fire detection systems
- Visual inspections by damage control teams
- Limitations
  - Exposes personnel to hazardous conditions
  - Long delay time for situational awareness
  - Requires significant human involvement

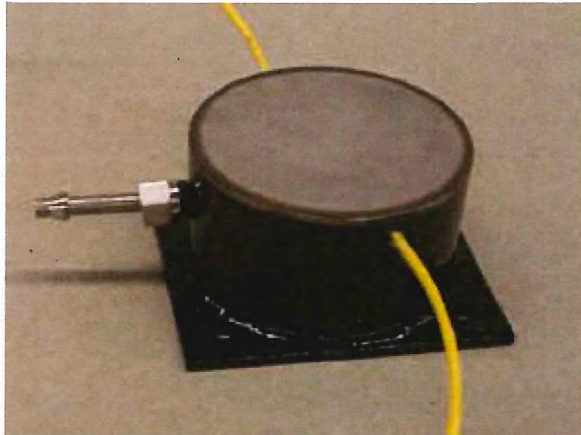




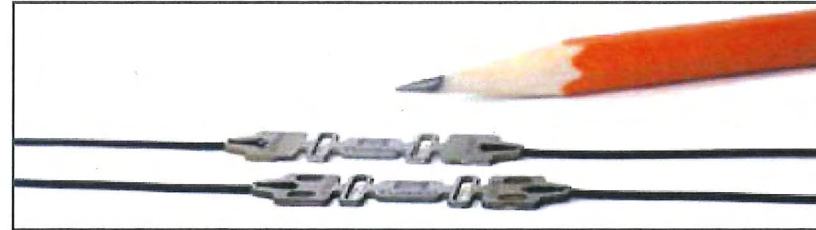


| Features   | Benefits   |
|--|--|
| All fiber optic sensors                                | No electrical power to sensor required,<br>Immune to RF interference |
| Ship wide distributed sensing<br>(multiplexed sensors) | Fast replacement, retrofit   |
| Multiple sensor types on a single lead<br>cable        | Reduced cabling and installation time                                |
| Central processing system                              | Real-time data collection and analysis                               |
| Temperature sensor                                     | Fast response rate   |
| Flooding sensor  | Perform ship listing measurements                                    |

Flooding Sensor



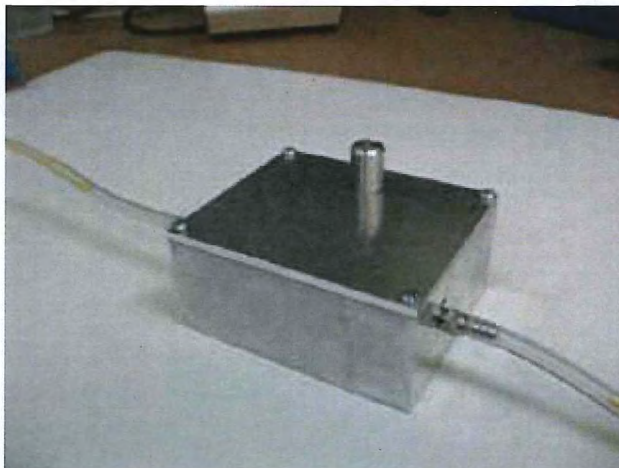
os3100 Strain Sensor



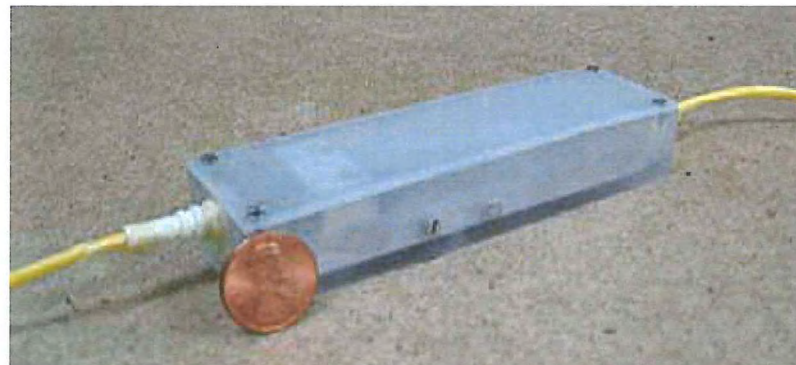
Fire/Temperature Sensor



Door Closure Sensor



Accelerometer

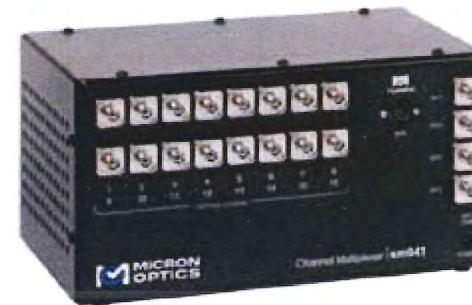




si425-500



sm041-416





- Results
  - By eliminating in-person investigation of alarm events, the ship's damage assessment personnel will quickly have a complete picture of the ship's condition, thus increasing the likelihood of surviving and recovering from the attack in less time and with less overall damage.
  - The automated assessment of the ship's condition will also improve the operational readiness of U.S. Navy forces.
  - The realization of reduced manning in U.S. Navy ships will reduce the overall operations and support (O&S) costs for the fleet.
  
- Acknowledgements
  - U.S. Navy
  - Aither Engineering, Inc.  
Tel: 240-296-1300, email: [info@aitherengineering.com](mailto:info@aitherengineering.com), web: [www.aitherengineering.com](http://www.aitherengineering.com)
  - Micron Optics, Inc.  
Tel: 404-325-0005, email: [info@micronoptics.com](mailto:info@micronoptics.com), web: [www.micronoptics.com](http://www.micronoptics.com)



# PRODUCT INFORMATION

Global Maritime Engineering

123 456789 101112 131415 161718 192021 222324 252627 282930 313233 343536 373839 404142 434445 464748 495051 525354 555657 585960 616263 646566 676869 707172 737475 767778 798081 828384 858687 888990 919293 949596 979899 1000000

Product  
Information

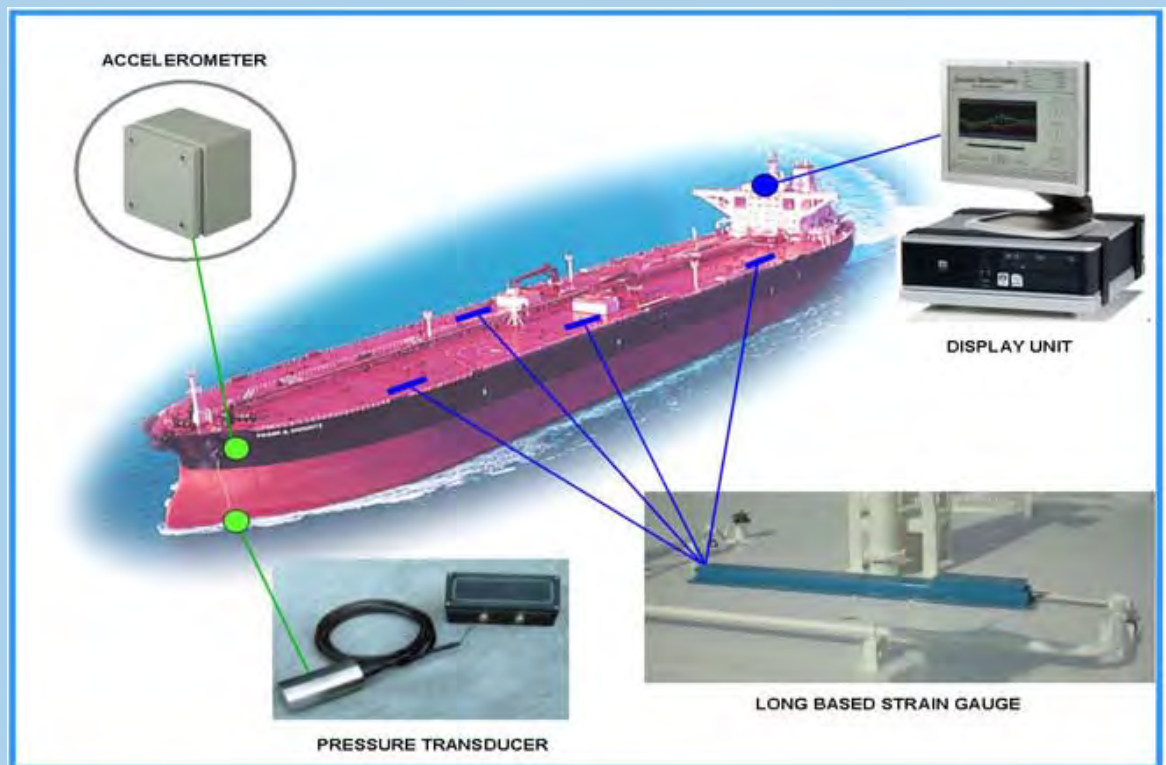
## STREMOS (HULL STRESS MONITORING SYSTEM)

Recently, the concern in the safe operation of ships has increased with respect to the safety and the life of ships and the prevention of marine pollution at the sea.

The frequent loss of bulk carriers and tankers during the late 1980's have brought about taking of strategic steps to improve the safety of such ship.

Under the circumstances of these heavy losses, the IMO (International Maritime Organization) approved the recommendation for fitting the hull stress monitoring systems for the improvement of the safety of ships of 20,000 dwt and above, carrying dry cargo in bulk.





STREMOS - Hull Stress Monitoring System has been developed for maximum efficiency of vessel operation and safety and provides the real-time information to the ship's master on the ship during navigating, loading and unloading operation, and also provides an alarm indication as necessary, indicating excessive stress on the hull.



## BENEFITS



Prolonged vessel life by reductions of structural damages and fatigue cracking

-  Early warning to avoid non-recoverable structural damage
-  Cost reduction for repair and maintenance
-  Improvement in ship scheduling and optimization of voyage times
-  Reduced insurance premiums during vessel's entire life time

## **SYSTEM DESCRIPTION**

STREMOS - Hull Stress Monitoring System is a sophisticated tool that provides the ship's master with the real-time information on the status of the ship's structure during cargo operation in harbour as well as during voyage.

The system monitors the stresses at four locations using specially designed strain gauges, and a bow acceleration and bow slamming pressure. In addition, the information on the navigational condition and environments are provided from the GPS, and a wind indicator etc.

This monitored information is displayed on computer screen. Also, the appropriate alarm signs are provided when the hull conditions exceed the prescribed criteria.

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STREMOS (HULL STRESS MONITORING SYSTEM)

DISPLAY

General Status

This is the most general display and is primarily used as an overview of the system. The outputs from the sensors (4 strain gauges, and an accelerometer) are displayed by the bar graph representing maximum and minimum values over previous 1 minute.

The mean, maximum and minimum values of gauge signals are displayed as the percentage values with respect to the prescribed criteria values.

In addition, the current date, time and global position are displayed by text. Ship's speed, heading and shaft speed are displayed in the form of clock gauge.



Bending Moment

This display shows maximum values of the vertical bending moments for both sea and harbour operating conditions as the percentage values with respect to the prescribed critical values.

The screen shows the bending moment trend over last 4 hours with the updated data every 5 minutes in the form of bar graph. Displayed time interval can be changed from 1 to 4 hours by selecting the option button.

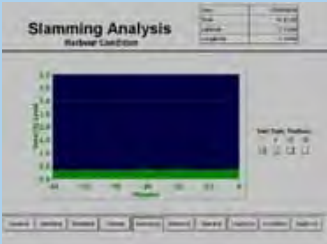
There are two kinds of display modes of bending moment, those are, SEA and HARBOUR modes.



Slamming

The Slam Warning is to warn the vessels operating personnel in advance that the vessel is in sea state or operating conditions approaching those that could have wave slams that could lead to either local or hull girder structural damage.

Slam warning monitors are to show the trend over time in relation to the slam wave impact that would exceed the selected warning levels.

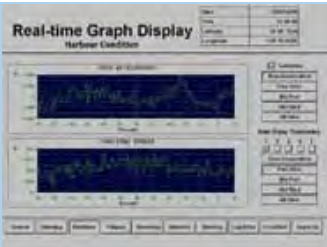


Real-time Display

The outputs from each sensor over the last 60 seconds are displayed on the two graphs when the button is clicked. The typical display is shown below.

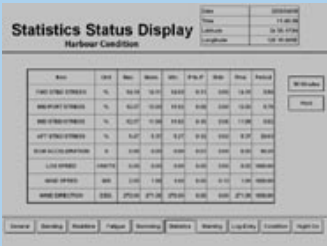
Items to be displayed on the two graphs are selected by clicking the gauge

selection button. Because two kinds of signal are displayed at once, user can compare one signal with another.



Statistics

It displays the results of statistical analysis performed on the data measured from all sensors during the last 5 and 30 minutes by selecting the toggle button in the upper right side in the figures.



As the statistical results, the following values are obtained and stored automatically on the computer hard disk for analysis ashore.

- Maximum +ve and -ve values
- Mean value
- Maximum peak-to-peak values
- Standard deviation
- Root Mean Square values
- Average zero crossing period

Fatigue Display

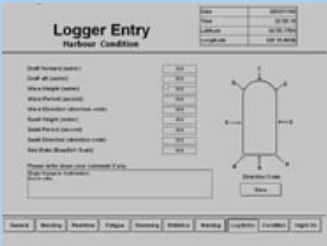
This display shows the cumulative stress cycle counts in the whole life of the ship and the fatigue cycle from a S-N curve in ABS rule. In this program the S-N curve is selected for F case to describe the longitudinal bulkhead and the deck plate at the long based strain gauges



Logger Entry

The Logger Entry display is designed to acquire a manual entry log of critical data extracted from the ship's written log book.

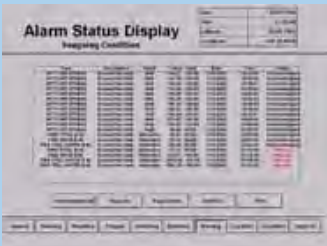
The related data from the ship's log are recorded in the computer storage disk for analysis ashore.



The manual entry data are recorded in the computer when the SAVE button is pressed after completion of manual key-in.

Alarm

When the alarm levels are exceeded in some condition, the contents of the alarm are displayed on the screen. The display of the past alarm history is available only for those on three pages volume.



The past alarm contents are automatically stored in the computer hard disk.

Replay

The logged data in the system computer during a voyage can be replayed by the software program called STREMOS-Replay.

This takes a similar form to the real time graph described above.

STREMOS-Replay software can be loaded on any IBM compatible PC with a suitable specification and can be run by loading the logged data from a ship via floppy disk or CD.

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## **Appendix C HULLMOS®, Rouvari Oy / HMC / Sirehna**

(6 pages)

UNCLASSIFIED



SOPHISTICATED HULL STRESS MONITORING SYSTEM

**HULLMOS®**

**WHY SETTLE ONLY FOR ESTIMATES  
ON YOUR VESSEL'S HULL LOADING  
WHEN HULLMOS CAN GIVE YOU  
THE FACTS?**





# HULLMOS®

## – INVESTMENT FOR YOUR VESSEL

HULLMOS® is part of owners risk management. It enables risk control in the fields of:

### SAFETY

HULLMOS® has especially been developed to protect the hull thus minimising risks for hull failures. The system alarms when there is a risk of damage to the hull structures or cargo caused by improper loading or high speed in heavy weather.

### HULL MAINTENANCE

HULLMOS® is a top of the line real-time recording system, which saves the lifetime history of a vessel. The gathered information assists in hull condition evaluation and fatigue life assessment thus giving the possibility to prevent cracking and more severe casualties. In addition to that the gathered data is useful when planning hull inspections and maintenance.

### ENVIRONMENT

Negative publicity is always inevitable in serious shipping disasters. Costs for these disasters are enormous in terms of money and values of nature, not to mention the impacts

on a company image. Use of HULLMOS® clearly increases safety of sea transport and it might have prevented many of the spills and more severe environmental catastrophes.

### ECONOMY

Installing HULLMOS® on board gives the shipowner a viable opportunity to negotiate a lower insurance premium. The system also helps in keeping the hull in good condition, which brings about reduced repair and maintenance costs and extended vessel life. As a running recorder the system also enables the shipowner to monitor the handling of the vessel when chartered.

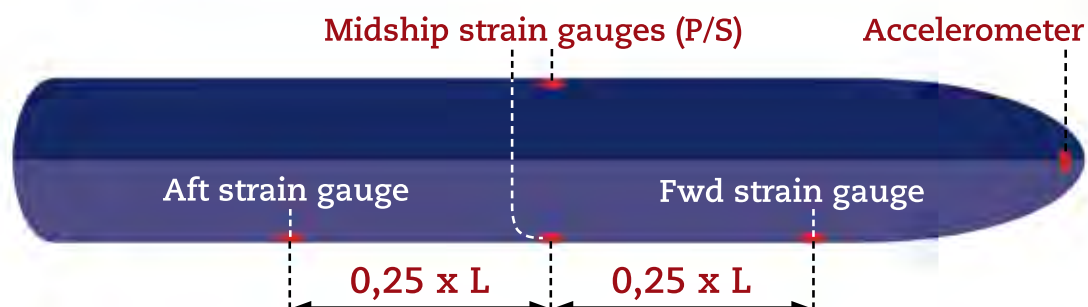
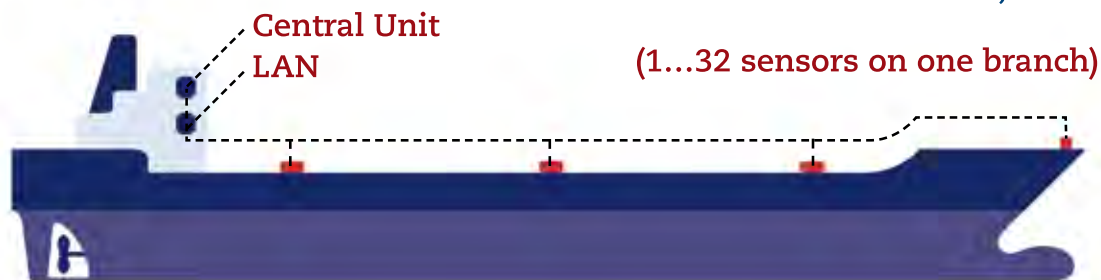
### PROBLEM SOLVING

HULLMOS® can serve as a practical tool in problem solving cases. HULLMOS® is suitable for long-term and short-term testing periods as it is quick to install, it provides data instantly and gives possibility to process and analyse the gathered data afterwards.

# HULLMOS®

## MONITORING SYSTEM

Typical sensor locations, class notations: ■ HMON-1, DNV  
■ SEA (Hss-4), LR  
■ HM2+R, ABS





# ADVANCED MARITIME SAFETY

Without hull monitoring there is no knowledge of the actual strains the vessel is experiencing. In the past the only way to make vital decisions has been based on assumptions of optimum speed and direction. In modern shipping industry Hull Stress Monitoring System HULLMOS® provides warning, assistance and predictions to the captain in real-time. The versatile benefits of HULLMOS® makes it clearly a significant part of today's advanced maritime safety.

## SOPHISTICATED HULL MONITORING SYSTEM

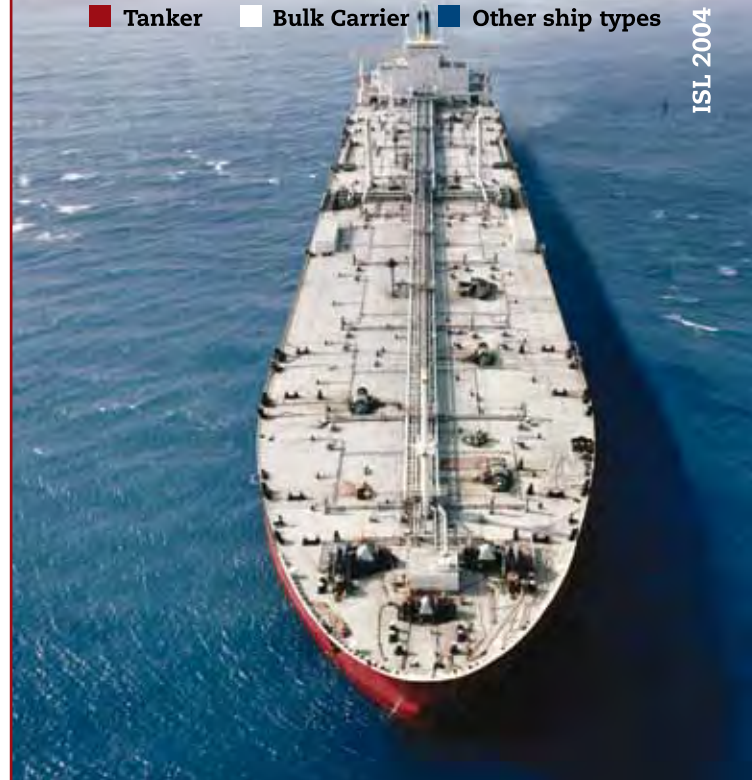
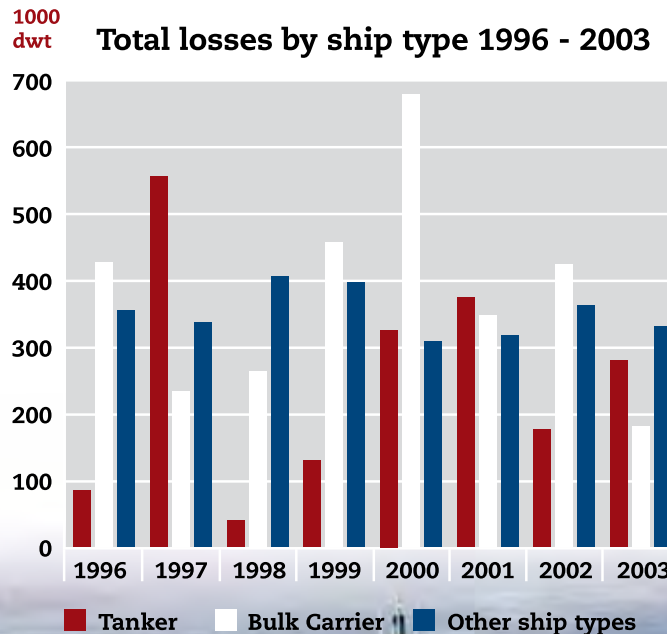
The system is ideal for versatile measurements and monitoring tasks of a ship hull:

- Standard HULLMOS® strain monitoring system with a class notion such as LR, DNV, ABS, BV
- Tailor-made hull monitoring solutions
- Solution for many problems associated with hull structures

## HULLMOS® CONFIGURATION

HULLMOS® includes a range of measuring and monitoring products for both steel and aluminium structures. Typical HULLMOS® system consists of 4-6 sensors on the main deck, one accelerometer on the bow and a central unit on the bridge. HULLMOS® can easily be integrated with other information systems on board.

Based on relative deformation the sensors measure and analyse values of global longitudinal bending stresses as well as vibration of the hull girder. The gathered data is then transmitted to the central unit to be further analysed, displayed and datalogged. The personnel in the bridge will be alarmed to take actions in order to avoid exceeding of design stresses.



Length 100mm



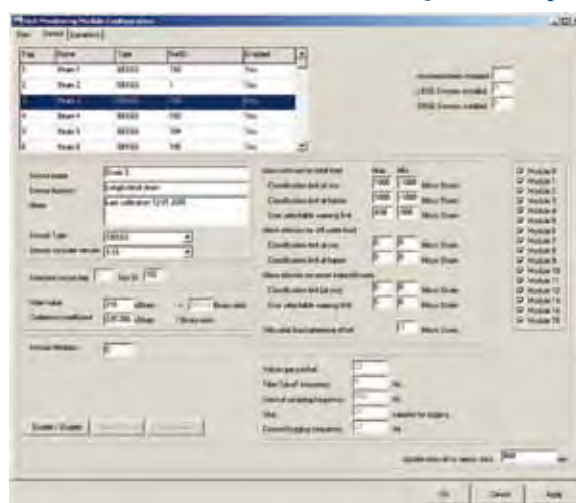
## SBSG

The intelligent small size sensor is highly accurate and offers an unique option for continuous stress monitoring even in cumbersome locations. The factory calibrated SBSG sensor is compact and reliable in use. Furthermore, it is easy to install and needs no maintenance.



HULLMOS® can be installed both on old vessels and newbuildings on all types of ships including e.g. Bulk Carriers, Oil Tankers, Product Carriers, LNG Carriers and FPSOs.

### User Interface: Configuration Display



|                             | SBSG (F)  | LBSG (F)            |
|-----------------------------|---|---------------------|
| <b>Resolution</b>           | 5 microStrain   |                     |
| <b>Bandwidth</b>            | 0 ... 150 Hz  | 0... 5 Hz           |
| <b>Linear Range</b>         | +/-1200 microStrain   | +/-2000 microStrain |
| <b>Max. Dimension</b>       | 130 mm  | 2420 mm             |
| <b>Supply</b>               | 12 ... 24 VDC   |                     |
| <b>Degree of Protection</b> | fully sealed  | IP 56               |
| <b>Cabling</b>              | RS 485, shielded cable, twisted pair  |                     |
| <b>Exi</b>                  | with Zener Barrier  |                     |
| <b>Temperature Range</b>    | -25°C ... +70°C   |                     |
| <b>Vibration durability</b> | <ul style="list-style-type: none"> <li>Frequency Range 3 ... 13.2 Hz:<br/>Amplitude 1.0 mm (peak value)</li> <li>Frequency Range 13.2 ... 100 Hz:<br/>Acceleration Amplitude 0.7g</li> </ul>  |                     |
| <b>Baud Rate</b>            | 1.25 Mbps or 625 Kbps   |                     |
| <b>Interface Protocol</b>   | ARCNET  |                     |
| <b>Output</b>               | <ul style="list-style-type: none"> <li>Signal Mean Value</li> <li>Signal Standard Deviation</li> <li>Signal Peak Values</li> <li>Average Mean Crossing Period</li> <li>Rainflow count</li> <li>10 second Signal History in Cyclic Buffer</li> </ul> |                     |

(F) Fibre Optic version available with tailored characteristics

## LBSG

Length 1700mm



ROUVARI OY  
Musekatu 9 B, 00100 HELSINKI, FINLAND  
E-mail: info@hullmos.com  
Web: www.hullmos.com  
Tel. +358 505615871





# SHIP MOTION AND HULL MONITORING SYSTEM

## Strain, motions and sea state estimations functionalities

Based on the HULLMOS® system

### Applications

- Frigates
- Aircraft carriers
- Landing ships
- Fast patrol boats
- Bulk carriers
- Tankers
- Cruise vessels

**SYSTEM AVAILABLE FOR  
INSTALLATION AND  
IMPLEMENTATION  
ON-BOARD ALL KINDS  
OF VESSELS**

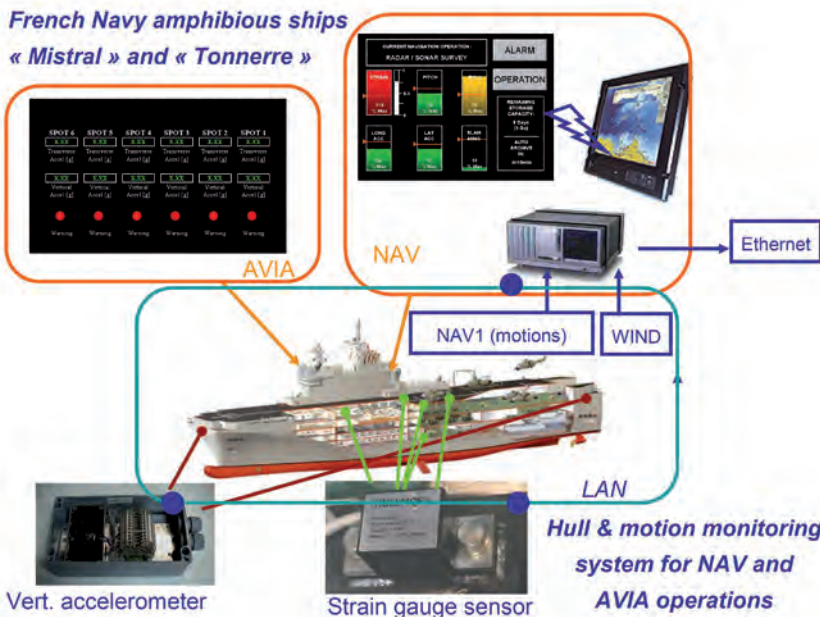
**SEA-STATE ESTIMATION  
MODULE**



# SHIP MOTION AND HULL MONITORING SYSTEM

## KEY POINTS

### French Navy amphibious ships « Mistral » and « Tonnerre »



- Sirehna has developed a complete ship monitoring system including strain, motions and sea-state estimation functionalities. This system is now available for installation and implementation on-board all kinds of vessel.
- Based on the HULLMOS© system, the ship monitoring system records

measurements of hull stresses and motions in various ship locations. These data are processed in real time to deliver criteria for assisting the ship navigation and operations onboard. The system can generate alarms when these criteria exceeds predefined thresholds and thus give warnings of risk of damage to the hull structures resulting from an improper loading or from improper

speed in heavy weather for instance. The system also allows to record data over the vessel lifetime history. The gathered information represents a precious aid for hull strength evaluation and fatigue assessment.

- HULLMOS© system is composed of strain sensors mounted on the ship main longitudinal girders, of one or two accelerometer(s) and of a central unit on the bridge. It can also be provided with a ship motion measurement unit and be easily integrated with other information systems on-board.
- A Sea-state estimation module, based on the analysis of ship responses (mainly motions) on waves complements the system.

## Potential extensions

- Decision-making tool for AVIA and other applications (replenishment at sea,...)
- Operating Guidance System for route and operation optimisation

## REFERENCES



- HULLMOS system has been installed on more than 20 ships from 2000: chemical tankers, high speed craft, oil tankers, yachts, cruise ships, etc.
- Complete monitoring systems, including analysis and display modules for assistance to navigation and AVIA operations, have been installed on the two French Navy's amphibious ships (Tonnerre and Mistral BPCs) in 2005.

### SIREHNA

1 rue de la Noë - BP 42105  
F-44321 NANTES Cedex 3  
tel: + 33 (2) 51 86 02 86  
www.sirehna.com



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## **Appendix D CPE Systems**

(3 pages)

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# Stressing the Point

## hull stress monitoring system

test & measurement

custom electronics

engineering software

data management



defence & aerospace

consumer goods

environment

mining

ICT

energy

agriculture

biotechnology

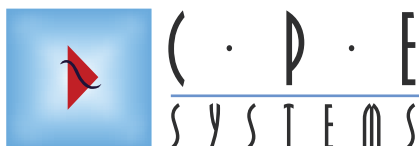
transport & automotive

## Challenge

The Australian Navy required a system to monitor the condition and dynamic forces on the hulls of its two LPA class ships, the HMAS Kanimbla and the HMAS Manoora. These ships are used to transport and support up to 450 troops, their vehicles and equipment, as well as four Black Hawk helicopters and two landing craft.

HMAS Kanimbla and HMAS Manoora have done more than 40 years of service, and are still required to operate under all weather conditions, often with large amounts of vital equipment and personnel on board. A hull stress monitoring system was needed to inform the ship's crew as to the current and projected forces on the hull, so they can continue to safely operate the ships.

Apart from sending real-time alarms to the crew as the hull stress approaches or exceeds the damage threshold, the system must also keep a comprehensive data log so that developing trends can be determined, and decisions made to prolong the service life of the ships.



## Solution

CPE Systems, in collaboration with Endurance Consulting, designed and implemented a custom built hull stress monitoring solution, with an easy to use software interface running on a touch screen panel PC mounted in the ship's bridge.

The software was developed in LabVIEW due to its quick implementation time and ability to interface with all of the necessary sensors. The system simultaneously monitors four stress sensors, two accelerometers, starboard and port motor rpm and wind conditions. Raw data and statistics for all sensors is stored with up to five years of data available for review and export.

By touching areas on the screen, recent history and up to 24 hours of statistics for each stress sensor or accelerometer are displayed. Probability of reaching a threshold or predicted time to reach threshold is also displayed along with each sensors current state.

The project was completed under an extremely tight timeframe, with software development and verification, two sets of hardware installs, and two sets of sea trials being completed within three months.

For more CPE user solutions, visit our website.

[www.cpesys.com.au](http://www.cpesys.com.au)



# Hull Stress Monitoring System

## real-time safety and structural data analysis

Prolong ship lifetime and reduce maintenance costs with the Hull Stress Monitoring System (HSMS). CPE's HSMS provides real-time monitoring of the forces exerted on ship's hulls. It provides immediate feedback to the crew if hull stress or fatigue levels exceed safe thresholds, and reduces maintenance costs by avoiding or reducing the risk of structural damage to the vessel.

Designed and verified to meet DNV criteria for Hull Monitoring (HMON), the HSMS includes strain sensors that measure the global loading level, plus a bow accelerometer used to detect slamming incidents.

Optional sensors include local strain, motion, pressure and temperature. Also, inputs from the loading computer, GPS, propulsion system and wind speed and direction can be added.

## Key Features

- Reduces the risk of extreme hull loading
- Analyses raw data to present time trends of hull stress and fatigue
- Calculates the probability and predicted time to reach alarm thresholds
- Simple, intuitive user interface
- Allows ship operators to make decisions that will prolong the service life of the vessel
- Logs up to 5 years of data
- Exports raw and statistical data to excel or text format

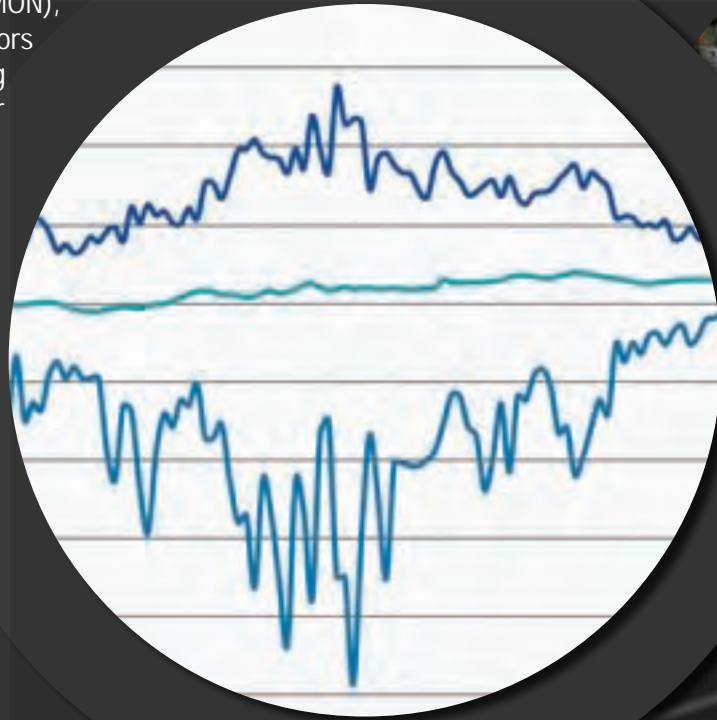
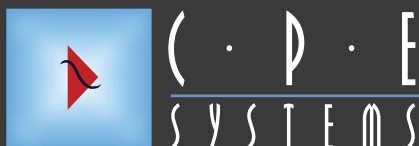
## Test Systems

Engineering & Scientific Software

Data Management & Presentation

Control, Automation & Vision

Structural Health & Condition Monitoring



[www.cpesys.com.au](http://www.cpesys.com.au)



# Hull Stress Monitoring System

## specifications

### Standard Components

- 4 x Strain Sensors to capture the global loading level, monitored at 20Hz
- 1 x Bow Accelerometer to capture slamming events, monitored at 500Hz
- 12 inch industrial touch panel PC for displaying current data, historical trends and alarms
- Windows embedded operating system
- Data Acquisition Hardware
- IP 66 rated steel enclosure for computer, power supplies and data acquisition hardware
- Uninterruptable Power Supply (UPS) to allow 30 minutes of operation without external power

### Optional Components

- Additional strain and/or acceleration, GPS, temperature, pressure, motion or other sensors
- Connection to existing instruments such as navigation, propulsion, loading computer and wind instruments
- Remote access to data and reports
- In Service Support

### Bridge Console

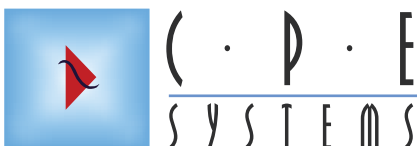
The console on the bridge features a 12 inch industrial panel PC running the HSMS software package. The software is designed for ease of use and ensures that important information can be easily accessed and interpreted.

The HSMS software package includes:

- A main screen where the stress, fatigue and alarm status of each sensor is displayed on a plan of the ship
- Statistical calculations and logging of stress, slam detection, mean, minimum, maximum, standard deviation, skewness, kurtosis, mean zero crossing, fatigue (percentage of ship life remaining), probabilities of excessive stresses and slams, and predicted time until limits are exceeded
- Click on any sensor in the ship plan to see historical and statistical trends of the data
- Visual and audible alarms when stress and slam limits are exceeded
- Visual and audible alarms when stress and slam reaches 80% of limits
- Click on an alarm to see a historical log of all alarms
- A "Test Alarms" button
- An area for manual data input for ship loading parameters, sea state, location and heading
- A button to save the last 5 minutes of raw data in-case of an incident. This logs all data-points at their acquisition rates of 20Hz for strain and 500Hz for acceleration
- A button to upload all data to USB for export to excel or text format

### Installation

Installation of all sensors and hardware is included. This includes calibration of all sensors and data acquisition hardware, and a period of verification to ensure the system is acquiring accurate and reliable data. After installation, all calibration certificates, hardware specifications and instruction manuals will be delivered.





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**Appendix E Naviscan (HSMS), Korea Marine  
Technology Co., Ltd / Sea Structure Technology Co.  
Ltd**

(15 pages)

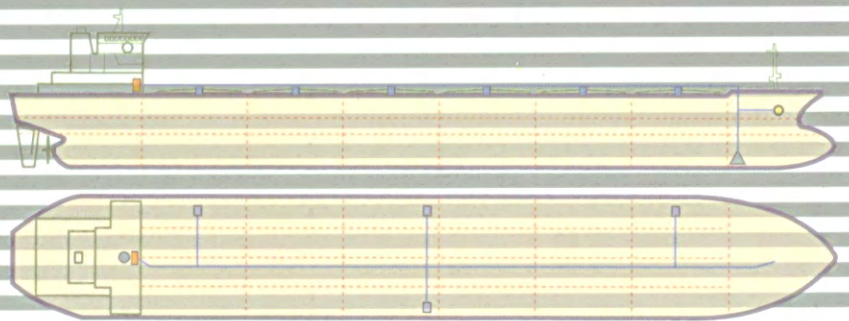
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# KMTC

## HULL STRESS MONITORING SYSTEM

TOTAL MARINE EQUIPMENT & GAUGING KOREA MARINE TECHNOLOGY., LTD CO



KOREA MARINE TECHNOLOGY CO., LTD

**KMTC**  
TOTAL GAUGING & MARINE EQUIPMENT





### **Hull Stress Monitoring System** *for providing real-time information on ship motion and global stress during navigation and loading/unloading operation.*

#### **NaviScan Object**

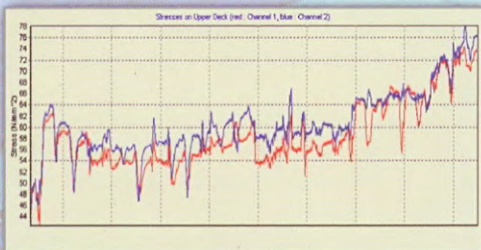
A modern ship today has many different safety systems installed.

All of these different systems ensure optimal safety on the ships voyage.

However, none of these systems indicates any condition on the hull safety.

NaviScan gives real time information on dynamic stress from several sensors monitoring the hull condition.

Ships staff can minimize the hull stress during ships sailing, loading and unloading.



During cargo loading/unloading, the NaviScan is online with ship's local calculator combining LC(Loading Computer system) information and data from HSMS(Hull Stress Monitoring System) sensors guide the crew through a safe loading and unloading procedure.

- Adjust during ship operation
- Deviation from hull specific guidance gives alarm to the bridge.

NaviScan complies with all Classes notations.

- HMON-2, DNV
- SEA(R), LR
- HM2+R, ABS
- HMS-2, KR



Since 1999, KMTC has been developed to ensure uncompromising spirit for quality and customer service, and it has committed itself to being a true leader in the field of Level Control.



**Reference for HSMS**  
40 Ships Installed (2001~2008)

### NaviScan Features

- Measurement of hull stress
- Measurement of ship motion and slamming
- Interface with loading instrument for initial calibration of sensors
- Intrinsic safety system
- Easy recalibration procedure





Pc & Monitor, Keyboard, Mouse, Printer

UPS

Amplifier

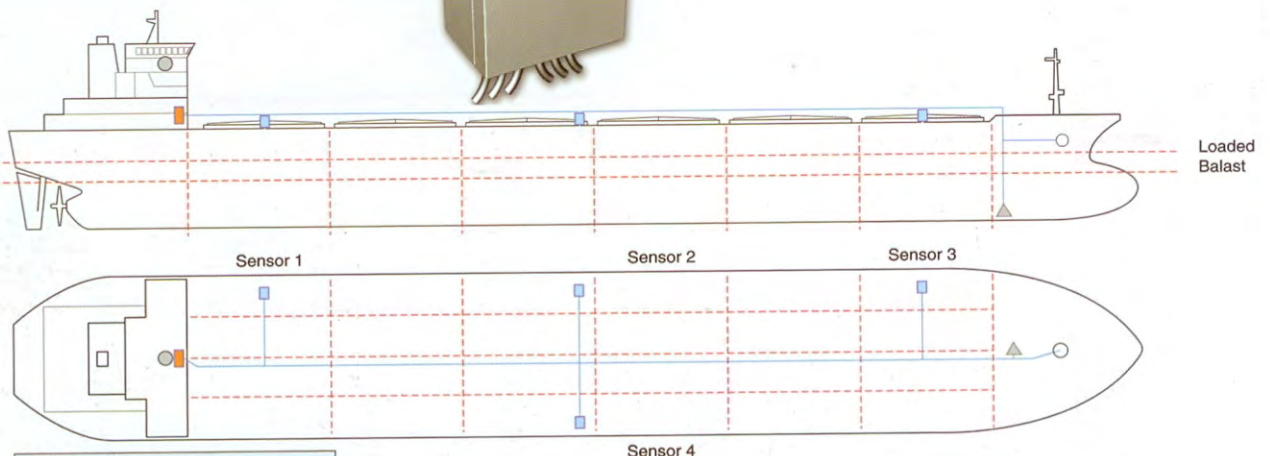
Clinometer

### A LBSG (Long Based Strain Gauge)

LBSG is a sensor to measure the longitudinal strain of hull girder. LBSG consists of a 2000 mm steel rod, which is fixed at one end and free at the other end, and LVDT (Linear Variable Differential Transducer) sensor.

### Accelerometer

An accelerometer is fixed to the vertical wall in bosun store, which measures the bow acceleration when the ship moves. The measured bow acceleration is compared with threshold velocity to indicate the probability of slamming in rough seas.



- LBSG Sensors On deck
- Temperature Compensation(option)
- Accelerometer
- Junction Box
- Measuring PC, Amplifier, Clinometer
- ▲ Pressure Transducer(option)



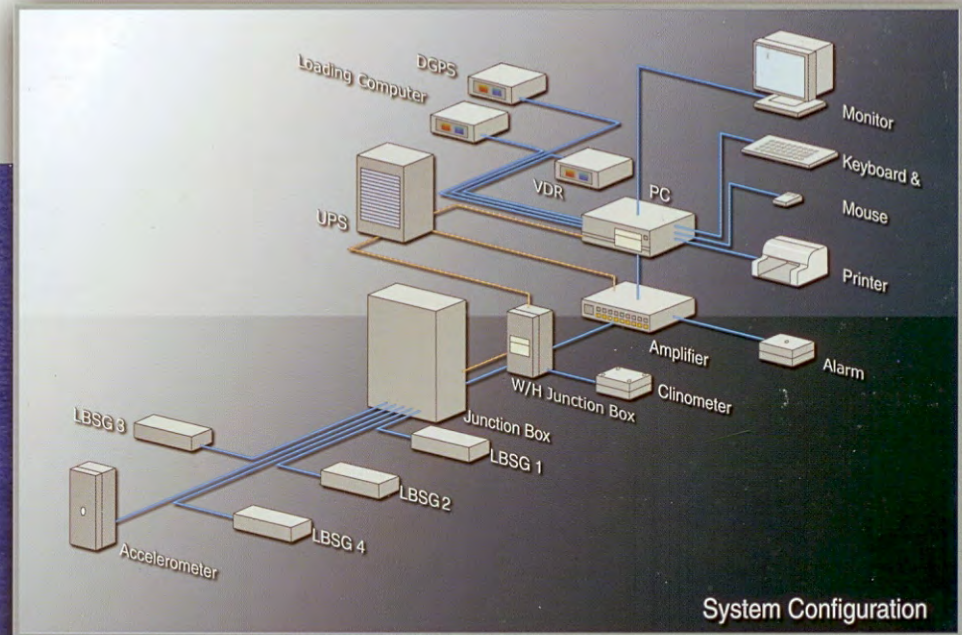
Since 1999, KMTC has been developed to ensure uncompromising spirit for quality and customer service, and it has committed itself to being a true leader in the field of Level Control.



Accelerometer

### Clinometer

The bi-axial clinometer is installed on the bridge deck and gives information about pitch and roll angles.



System Configuration

### Amplifier

The multi-channel amplifier converts and amplifies current input for voltage output. LVDT and accelerometer have pre-amplifier for converting the voltage input to the current output. And the main amplifier gives -10 to +10 volt output for 4 to 20 mA input with signal conditioning.

### Data processor, Display unit

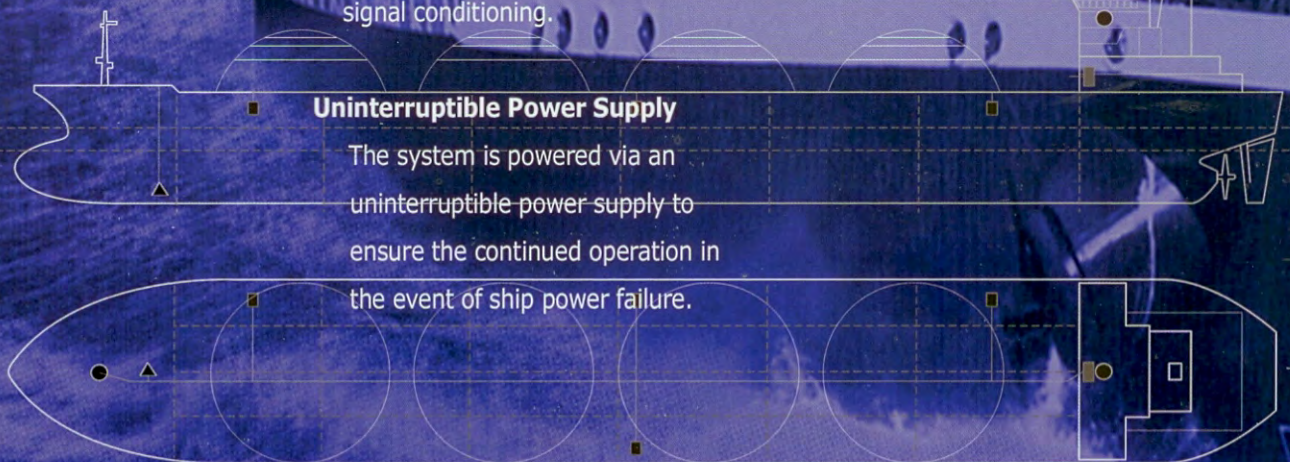
#### and Interface with external systems

Data acquisition and processing is carried out on a pentium PC with a internal A/D converter to process the sensor signals.

The display unit is a color monitor.

### Uninterruptible Power Supply

The system is powered via an uninterruptible power supply to ensure the continued operation in the event of ship power failure.







### GENERAL INFORMATION

- Real-time data given from the sensors (4 strain gauges, 1 accelerometer) are displayed on bar graphs which represent percentage of the permissible critical value.
- The stress histories trend for the last 4 hours are displayed, which represent five minute mean, maximum and minimum values.
- The current date and time are displayed.
- Representing alarm of LBSG, if it is not working, will be shown blinking (red foreground/gray background) about each sensors.
- Display critical sensor failure alarm incooperated.
- LBSG temperature sensors read expansion on SUS rod and forward it to Software. Yellow bars are of being temp. compensated. Blue ones are of not being compensated.



### VERTICAL BENDING MOMENT

Still water bending moment, wave bending moment and total bending moment are displayed for each channel. There are four different individual sensors giving conditions:

- SWBM(Still Water Bending Moment)
- WBM(Wave Bending Moment)
- TBM(Total Bending Moment)

If the measured stress level exceeds the allowable level, the external alarm indicator is activated.

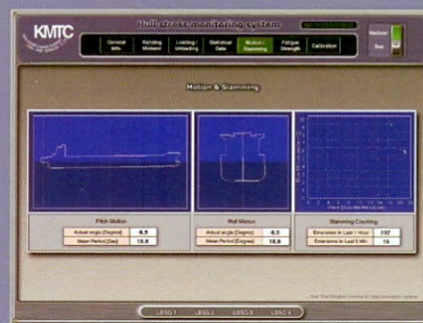
### LOADING AND UNLOADING

The bar graphs represent the mean stress values, which mean Still Water Bending Moment (SWBM). The permissible bending moment for both sea and harbor condition according to the classification rules are also displayed.

The bending moments from the ship's loading computer are also available both manually and automatically as an option. The table on the screen shows the measured values, actual bending moment by loading computer, permissible still water bending moment and their comparison results.



Since 1999, KMTC has been developed to ensure uncompromising spirit for quality and customer service, and it has committed itself to being a true leader in the field of Level Control.



## MOTION AND SLAMMING

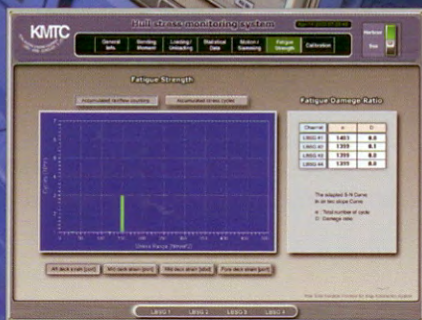
Roll and pitch angles due to ship motion are presented. The mimic ship model is animated according to the measured pitch and roll angles and the animation periods are the same as those of the measured roll and pitch.



## STATISTICAL DATA

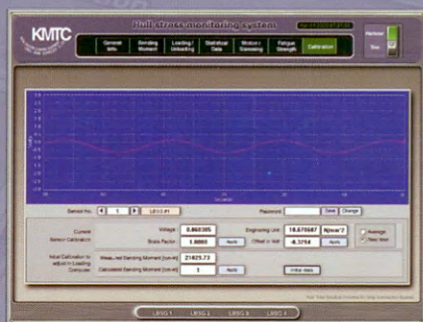
As the statistical results, the following values are collected and stored automatically on the computer hard disk for feed back.

- Maximum peak, Minimum peak
- Mean value
- Maximum peak-to-peak values
- Standard deviation
- Average zero crossing period



## FATIGUE STRENGTH

The counting is carried out using the rainflow method and stress range are divided into a number of blocks with a constant stress range of 10 N/mm<sup>2</sup>.



## CALIBRATION

For LVDT sensor the signal is initially calibrated in this display. Comparing the measured stress value with the calculated value, the offsets in the system are adjusted to these calculated values.

The users can input the calculated bending moment (ton-m unit) by loading computer in the edit box of "Calculated Bending Moment in ton-m", then, the offset value will be converted to the voltage unit automatically by clicking the "Apply" button.





### High Alarm System

High level alarm system  
High & Overfill Alarm System  
High level alarm system With temperature sensor  
Capacitance type high level alarm sys.



### Level Switch

Magnetic float-type level switch(horizontal/vertical type)  
Displacement-type level switch  
Reed switch-type float level switch  
Capacitance-type level switch  
Electrode-type level sensor  
Non-flow alarm switch  
Float-operated type level switch

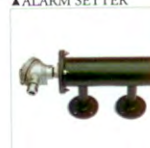


### Pressure gauge board panel(LNG,LPG)

### Pressure Gauge Panel(For Engine)



▲ALARM SETTER



▲LO SUMP TANK



▲LEVEL SWITCH

ACCUMURATED  
SKILL



▲LS FOR LO SUMP TANK



▲DRAIN BOX WITH LS



▲LEVEL SWITCH



▲ACCESSORIES



▲FLOW SWITCH



▲DRAIN BOX WITH LS



▲PACKAGED UNIT FOR UNIT COOLER

LONG  
LIFE  
SPAN



▲PRELUB OIL LEVEL SWITCH



▲LO SUMP TANK

ACCURACY



▲Voyage Data Recorder



▲Reefer Container Receptacle



▲EMERGENCY SHUT DOWN SYS.



▲EMERGENCY SHUT DOWN SYS.

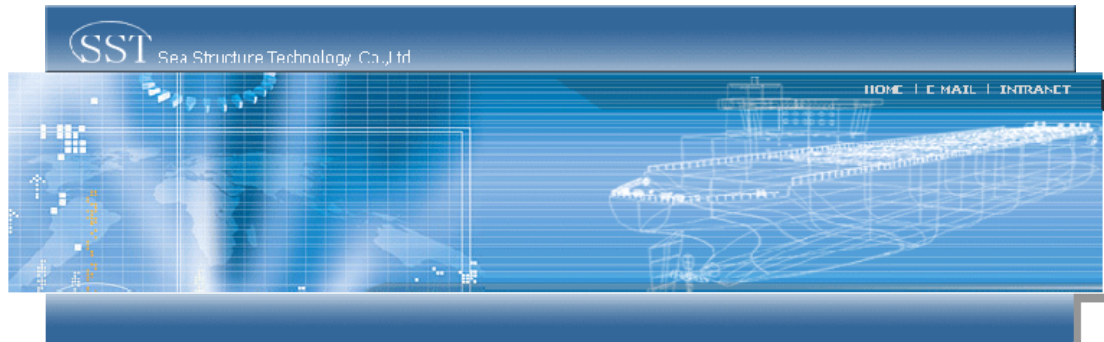


▲Hull Stress Monitoring System

KOREA MARINE TECHNOLOGY CO., LTD  
**KMTC**  
TOTAL GAUGING & MARINE EQUIPMENT

HEAD OFFICE & FACTORY  
350-1, Maegok-Dong, Buk-Gu, Ulsan, 683-420, Korea  
Tel : 82-52-282-7833, 7835 Fax : 82-52-282-7836  
<http://www.kmtcmarine.co.kr>  
[kmtc7880@kornet.net](mailto:kmtc7880@kornet.net)





#### ■ Hull Stress Monitoring System, Naviscan

The Naviscan is the navigation safety instrument which monitors real-time hull girder stress during a voyage or loading, unloading operation. The hull stress monitoring system (Naviscan) is designed to apply for wide range of commercial vessels such as LNG, LPG, Crude oil tankers, Bulk Carriers, Container vessels, etc. This enables crew members and ship owners monitor the hull in safe operation using LVDT sensors on deck. Based on the information provided by Naviscan, ship owners and crew members ultimately can minimize any damages by hull fatigue stress and optimize a voyage, ship management. Also, the system stores long-term data for voyage route optimization and for further research. It gives alarms when the induced stress goes over the pre-set allowable limit of 80 percent

The hull stress is one of the major factors which cause irretraceable damage to merchant marines. Fatigue accumulated in vessels leads to local cracks in the hull. Then, this might call very dangerous situations. For example, November 20th, 2001, crude oil carrier "Presige" broke into two pieces during a storm while navigating on Atlantic Ocean near Spain.



By the way, let's find another accident during unloading. In January 16, 2003, it happened to the vessels, container vessel "Troyburg" and Bunker Barge "PebbleBeach". While offloading at LA Berth 402, container was dropped onto tank barge alongside engaged in bunkering operations. One container accidentally lifted & hung up as two cones had been inadvertently left attached. Speed of cargo operations also played a factor.

The HSMS provides real-time information by continuous monitoring the hull fatigue stress. Please make sure that excessive hull movements can be resulted in cargo loss and damage to the vessel.



#### ■ Technology of HSMS, Naviscan

Naviscan gives real-time information on dynamic stress from 4 LBSG sensors at each location and monitors hull girder stress. LBSG sensors are located on deck to measure the longitudinal strain of hull girder. The LBSG consists of a 2000 mm steel rod, which is fixed at one end and free at the other end, and LVDT (Linear Variable Differential Transducer) sensor. The material of operating rod has the approximately same thermal expansion with the deck material. LVDT is the electrical transducer, with a full scale range of  $\pm 4\text{mm}$ , operating via the pre-amplifier with a 4~20 mA signal output to minimize external electric noise.

(Temperature Compensation Type only) As temperature on upper deck fluctuates, the temperature changes bring about thermal expansion or constriction on SUS rod of sensor. Then, this measured value by thermal expansion or constriction is calculated automatically. But, we have to realize that this calculated value is different from the real Bending Moment on hull of a vessel. So, the NaviScan who has PT100 temperature sensor on SUS rod compensates the differences and displays the real bending moment with applying thermal expansion

#### ■ The major features of Naviscan:

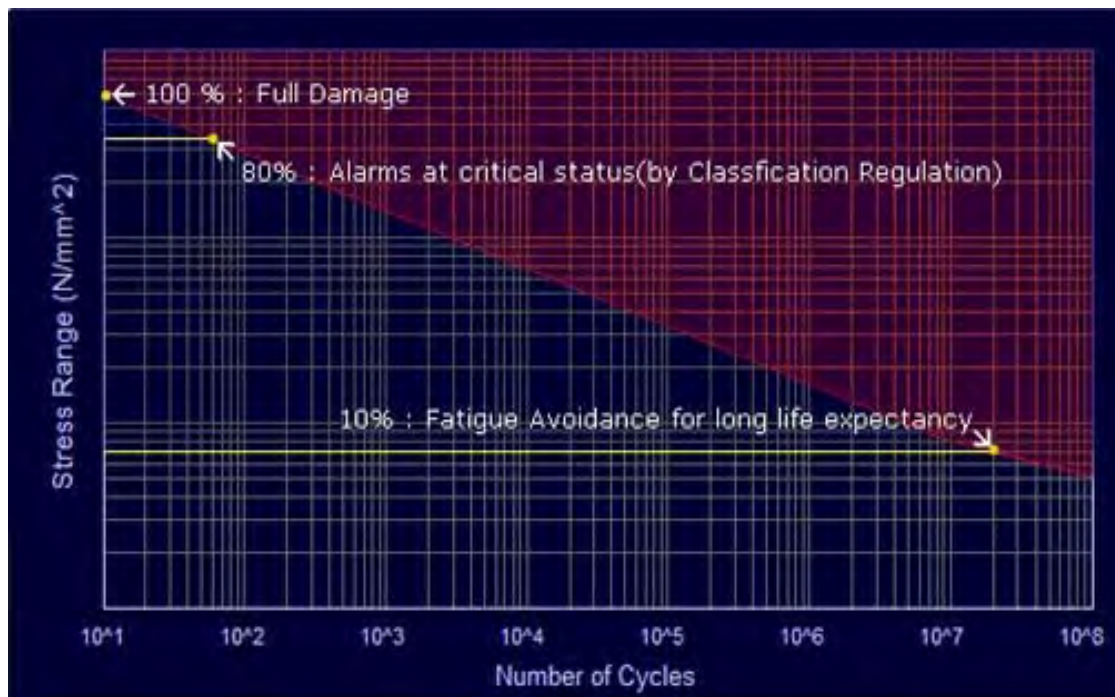
- Real-time monitoring for structural stability whilst navigation
- Globally combined stress display on heavy sea voyage
- Support for Sea Protest
- Real-time Display of Ship Motion Data
- Digital display for Rolling and Pitching
- Slamming reader
- Exclusive provider for Temperature Compensation Type (No competitor provides this type of system, even it is required by major classification)
- Ship Motion Display as standard function
- Application of Ex ia IIC T4 Type (Adopted Isolator for easy maintenance, not like other manufacturers' Barrier type)
- Operating System of Window XP (Other competitors' operates in Window NT version)
- PC storage for RS422 Interface Card

#### ■ Fatigue Strength on Hull

All of ships are designed with a given fatigue strength and the capacity shall be gradually reduced as it goes its maiden voyage. We can assume that the allowable fatigue shall be uniformly distributed over a vessel's life expectancy as shown in the curve (we take it for 20 years, based on experimental results by KR- Korean Register of Shipping), but, nothing actually goes its way upon a theory. There are many factors which might deteriorate the hull



life span like during loading, unloading or sailing on heavy sea weather. The HSMS helps crew members to monitor the current status on hull stress and to make faster decision for safe voyage. And, accordingly, shipping management can be controlled or advised through its accumulated data. Eventually, ship owners can avoid any extra cost for unexpected maintenance and plan for right repair procedures with free from hull damages. As you see the curve below, it shows that approximate 10 percent average stress will lead a ship life span to 20 years. And, accordingly, we can find how important to check real-time hull stress, because a ship life expectancy can be decreased if your crew members do not acknowledge or ignore the real stress on the vessel. In this vein, it won't be hard for ship owners to find the most economical way of fleet management.



#### ■ Applicable Vessels

The Hull Stress Monitoring System (Naviscan) is suitable for all types of ships which are to be monitored hull fatigue stress. Next are the following types of vessels which might be at risk of fatigue stress:

- Bulk carriers
- Oil tankers
- LNG
- LPG
- Container vessels

With installation of the hull stress monitoring system, Naviscan gives benefit to whom it may concerned:

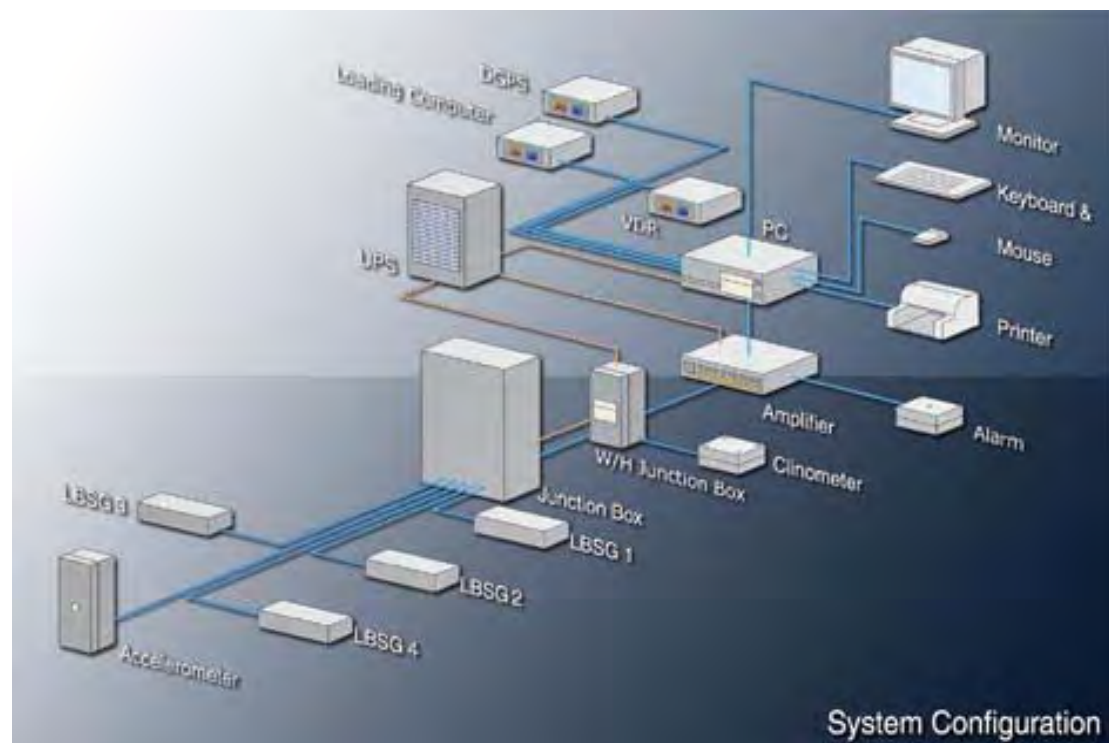
- Shipyards for structural improvements in designs.
- Naval architects for development of new designs.
- Classification Society for structural analysis
- Insurance company for claim evaluation through VDR.

### ■ Economical benefits with HSMS Installation

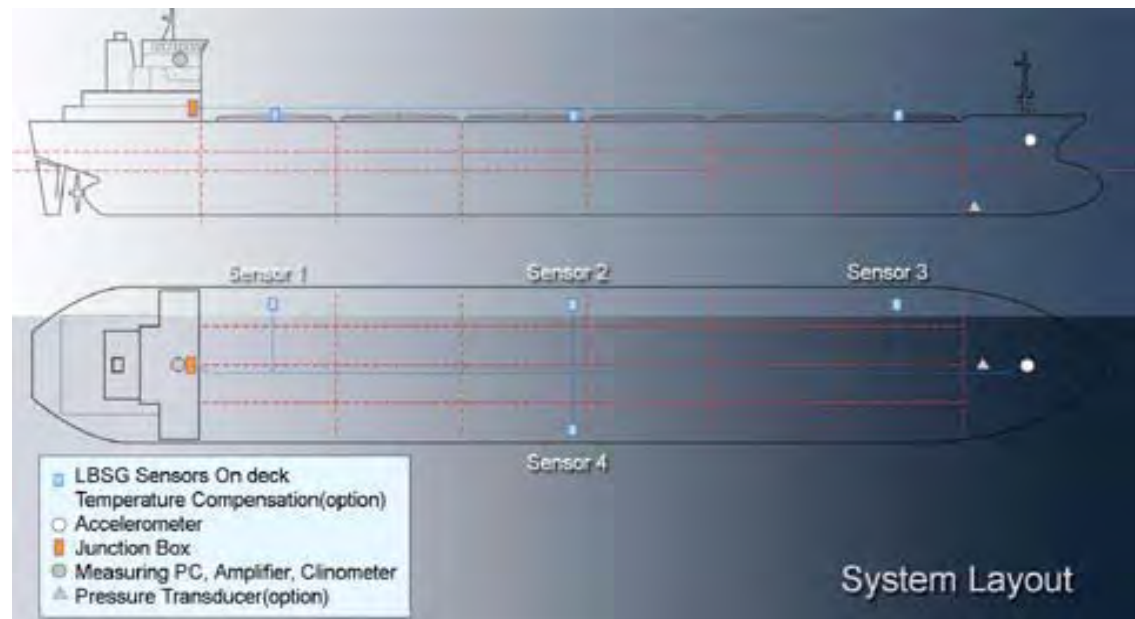
- Minimizing the depreciation of a ship's value
- Minimizing in loss of employment policy
- Reducing operation cost in maintenance
- Selling of a ship with non-excessive repairs
- Increasing Charter rates with better quality
- Lengthening the life expectancy
- Evaluating accumulated fatigue strength to vessels in trade market
- Easy maintenance with high efficiency
- Minimizing the uncertainty

## ■ System Configurations

Hull Stress Monitoring System (NaviScan) is the navigation safety instrument which continuously monitors real-time hull stress using deck-mounted LBSG (Long Based Strain Gauge), accelerometer and clinometer during a voyage or loading/unloading operation and it gives alarm as necessary. Based on the information provided, the ship master can alter the course or reduce the speed and the loading procedures can be improved. The long term data can be used for voyage optimization and further research.



## ■ System Layout



## ■ Major Classification Notation

- LR:SEA (R)
- DNV: HMON-2
- ABS: HM2+R, HMS
- KR: HMS-2
- BV, NK, RINA

## ■ Temperature Compensation Sensor (Optional)

As temperature on upper deck fluctuates, the temperature changes bring about thermal expansion or constriction on SUS rod of sensor. Then, this measured value by thermal expansion or constriction is calculated automatically. But, we have to realize that this calculated value is different from the real Bending Moment on hull of a vessel. So, the NaviScan who has PT100 temperature sensor on SUS rod compensates and displays the real Bending Moment with applying thermal expansion coefficient (SUS 304:  $1.73 \times 10^{-5} \text{ cm/cm/ } ^\circ\text{C}$ )

Technical specifications:

|                   |                           |
|-------------------|---------------------------|
| Temperature Range | -62 ~ +200 °C             |
| Type              | RTD and thermocouple      |
| Element           | Platinum 100 ohms, single |
| Insulation        | 3KV/min                   |

#### ■ Other Components

The Naviscan system consists of the following components:

- Main Amplifier
- Uninterruptible Power Supply
- Junction Box
- Alarm Buzzer
- Data Processor and Storage Unit
- Printer

#### ■ Interface (Compatibility)

The Naviscan system does interface with the following systems:

- Loading computer
- DGPS or Speed Log
- VDR (Voyage Data Recorder)

#### ■ Long Based Strain Gauge

LBSG Sensor is a 20mm stroke conductive plastic, linear motion potentiometer of which performance is unaffected by shaft rotation. Its co-mold element and precision construction allow this strain gauge to feature superb output smoothness and long life. It gives real-time local hull stress when a ship is on seagoing or at harbor.

#### ■ Electrical Specifications:

|                              |                                 |
|------------------------------|---------------------------------|
| Electrical Stroke            | 20 mm (F.S)                     |
| Total Resistance             | 0.1, 0.2, 0.5, 1, 2 kΩ          |
| Total Resis. Tolerance       | ±20%                            |
| Independent Linearity        | ±1%                             |
| Repeatability                | ±0.03%                          |
| Power Rating                 | 0.6 watt @ 70°C                 |
| Insulation Resistance        | 100 meg OHMS Min. @ 500 Vdc     |
| Dielectric Strength          | 500 Vrms, 50/60Hz, for 1 minute |
| Resistance Temp. Coefficient | 400 ppm/°C                      |

#### ■ Mechanical Specifications:

|                         |                        |
|-------------------------|------------------------|
| Mechanical Stroke       | 22 mm (F.S)            |
| Friction (Spring Force) | 300 gf Max. (3 N Max.) |
| Weight                  | Approx. 60g            |

■ Environmental Specifications:

|                       |                       |
|-----------------------|-----------------------|
| Operating Temperature | -40°C to +100°C       |
| Vibration             | 10 Gs, 500Hz          |
| Shock                 | 50 Gs, 11 mS          |
| Life                  | 5 million cycles Min. |

■ Accelerometer

Accelerometer is fixed to the vertical wall in Bosun store, which measures the bow acceleration due to ship motion. The measured bow acceleration is compared with threshold velocity to indicate the provability of slamming in rough seas

■ Technical specifications:

|                       |                                |
|-----------------------|--------------------------------|
| Type                  | Monolithic IC,                 |
| Measuring Range       | ±4g, (full scale range of ±5g) |
| Non-linearity         | 0.2%                           |
| Sensitivity           | 250mV/g                        |
| Frequency Response    | 3 Db Bandwidth: 12kHz          |
| Operating Voltage     | 2.7V ~ 5.25V                   |
| Operating Temperature | -40 ~ +85 °C                   |

■ Inclinometer

The bi-axial inclinometer is installed on the bridge deck and provides information about the pitch and roll angles. The electric sensor is a bi-axial electrolytic tilt sensor, which can measure tilting angle up to 20 degree within the frequency range of 4 Hz.

■ Technical specifications:

|                            |              |
|----------------------------|--------------|
| Measuring Range            | ±20          |
| Accuracy                   | ±0.06 / 10   |
| Repeatability at any angle | 0.01         |
| Resolution                 | 0.005        |
| Setting Time               | 500 ms       |
| Output Voltage             | 0.7V/20      |
| Supply Voltage             | ±15V         |
| TemperatureRange           | -20 ~ +70 °C |

---

Hull Stress Monitoring System

>>System Configuration

>>Software Configuration





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## **Appendix F Scimar, BMT Scientific Marine**

(2 pages)

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## Vessel Structural Monitoring

The Structural Monitoring System is a computer based system for monitoring the structural behavior of vessels during all phases of operation. The displays report stresses and motions in real time as well as providing alarms when values approach predetermined limits.



BMT can configure a structural monitoring system to meet any requirement. It can be installed on existing vessels, or integrated into “new build” and existing bridge consoles.

The structural monitoring system is easily networked to allow access from many locations such as the bridge, cargo control room, and the Master’s office.

Existing vessels can be retrofitted with either a stand-alone radar style console, or a small enclosure housing a computer for data processing and storage, and a flat panel display that mounts easily on a crowded bridge.

The basic system measures strain at mid ship, roll, pitch, bow vertical acceleration, and forefoot immersion depth, and integrates information from engine room sensors and GPS. The system can be expanded to include as many sensors as required.

Our systems are compact and easy to install, our innovative systems apply the newest technology at a competitive price and feature a flexible design to meet any vessel type and configuration.





## Features:

- Meets International Maritime Organization recommendations, all requirements of the US Coast Guard and the American Bureau of shipping for instrumentation and equipment operating in hazardous areas;
- Fully compliant with classification societies provisional rules and regulations for hull response monitoring and recording systems;
- Accommodates any number of client specified channels of sensor data;
- Real-time bridge displays provide ship masters with information regarding vessel structural behavior during all operations;
- Proven reliability through numerous years of TAPS and Asian– Pacific trade service;
- Simple installation and calibration procedures completed dock side, at anchor, or by riding crew.

## Additional Options:

- Additional strain gages, accelerometers, angular rate sensors, or inputs from other ship-board equipment can be added for specific vessel requirements;
- Vessel response calculator, WaveMAX, for predicting vessel motions, and bow emergence and slamming;
- A “black box” data recording system that allows continuous reporting of sensor data on non-erasable media;
- Calculate and maintain a record of cumulative ship fatigue damage;
- Shore based reporting via satellite data link;
- Multimedia based training on heavy weather ship handling;
- Integration of WNI/Oceanroutes’ Orion On-board Guidance System for satellite fed 10-day rolling weather forecasts to aide in avoiding difficult weather situations.

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## **Appendix G SENSFIB, Light Structures**

(11 pages)

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LIGHT STRUCTURES

SENSFIB

FIBER OPTIC HULL STRESS MONITORING SYSTEMS



# FIBER OPTICS FOR SAFETY AND RELIABILITY

Fiber optic monitoring solutions are gaining popularity in the oil and gas community due to the unrivaled performance and reliability. Light Structures' Hull Stress Monitoring System was the first fiber optic solution to enter the market, and has proven itself through several years' operation onboard shuttle tankers and VLCCs.

## SAFETY

Fiber optic Hull Stress Monitoring systems can be configured with absolutely no electrical components in hazardous areas. The low optical power means the system is intrinsically safe, even without introducing Zehner barriers or similar.

## RELIABILITY

Fiber optic solutions are immune to electromagnetic disturbance, which provides a stable, high-quality signal. With our well-tested installation technique our short-gauge sensors perform flawlessly without service, year after year. The system reliability has been optimized by the use of the Linux operating system, which is becoming the software of choice among computer professionals. All these factors contribute to our systems' high reliability and uptime.

## ACCURACY

Measurements are made using the wavelength of light, which enables high precision monitoring of stress. The precision is maintained all the way to the data logging, as the fiber optic signal is not affected by electromagnetic interference from adjacent signal or power cables. The accuracy is maintained over time by the use of an online reference in the signal receiver.

## COST EFFICIENCY

There is a small cost premium compared to alternative systems at the newbuilding stage, but this is countered through a reduced maintenance cost, which overall gives a lower system life-cycle cost. On LNGCs there are savings already at installation, as no welding is required for sensor mounting and the sensors do not require bulky casings.

## FLEXIBILITY

Sensors can be mounted on deck, on girders, submerged in ballast tanks or in void space. Systems can be configured in basic systems with only four strain sensors, or expanded to include fatigue monitoring sensors in the waterline, sensors in the bow for ice monitoring or local sensors for sloshing monitoring on tank walls.

# SENSFIB HULL STRESS MONITORING

The SENSFIB Hull Stress Monitoring systems from Light Structures AS promote a good and safe operation of the ship's hull. This is achieved by measuring the strain (hull load) in key locations. The HullInfo user interface can be displayed on a dedicated monitor in the wheel house, or run as third party software in integrated bridge systems.

**Ships that may benefit from  
Hull Stress Monitoring include:**

- Tankers; crude carriers and LNG carriers
- Bulk carriers
- FPSOs
- Container carriers
- High speed ferries and cruise ships
- Naval ships

**The system includes HullInfo, which is a dedicated  
console giving the officers on watch an objective  
measurement of the current conditions:**

- Hull loads and warning of load levels that represent an immediate threat to hull integrity
- Fatigue accumulation rates
- Trend predictions
- History data
- Parameters and warning levels for all connected sensors
- Environmental data



## SENSFIB MONITORING CAPABILITIES

## HULL GIRDER STRESS

The main function of Hull Stress Monitoring Systems is to advise the officers onboard on the stress in the main load-bearing longitudinals to avoid overloading, but this is not the only function of a modern HSM system.

# SLAMMING

Slamming, or hard wave hits, can seriously damage bow plating, and can be difficult to predict from the bridge. A vertical accelerometer in the bow is therefore included in all our HSM systems. In particularly harsh conditions a ship may experience bottom slamming, and some of our more extensive systems include sensors to characterize the bow re-entry load. Adding a strain sensor on a double bottom stiffener in the bow is a simple and maintenance-free alternative to bow pressure sensors that require penetration of the hull.

## WHIPPING AND SPRINGING

These resonant effects are receiving increasing attention from class societies as contributors to fatigue. SENSFIB HSM software can show users the load due to whipping and springing relative to other loads. Detailed information on these phenomena is also available to the owner onshore for operations and planning.

## FATIGUE

Along with corrosion, fatigue is an important factor in the wear on a hull, but unlike corrosion it is impossible to inspect for fatigue before cracking starts. With the good accuracy and reliability of fiber optic HSM we are able to monitor the fatigue build-up in the areas near sensors. For the best monitoring of side-shell fatigue, we recommend adding strain sensors on longitudinals inside ballast tanks in the waterline amidships.



The user interface can be configured to show current stress, fatigue accumulation, accelerations and slamming trend as well as sailing conditions in terms of sea state, wind, speed and position.

## ICE RESPONSE MONITORING

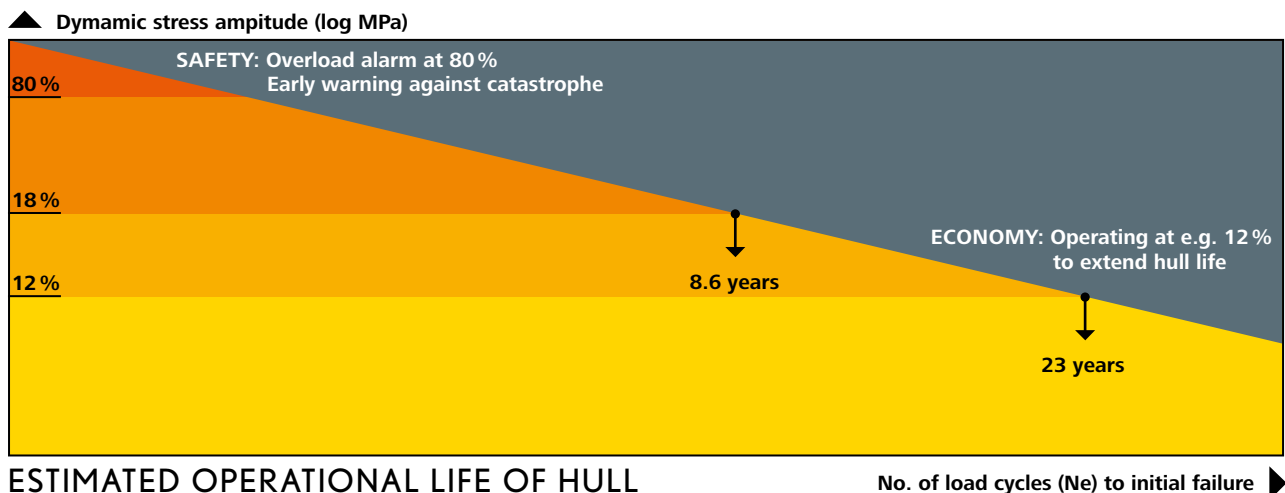
Warning of floating ice in cold waters can be included in the HSM system by adding strain sensors in the bow waterline.

## SLOSHING MONITORING

Non-intrusive monitoring of sloshing loads can be achieved by measuring the stress in the steel structures that support the containment system in LNG carriers or directly on the tank wall.

## MAINTENANCE PLANNING

When integrated in the inspection and maintenance procedures, the information from the HSM system provides valuable input to maintenance planning.

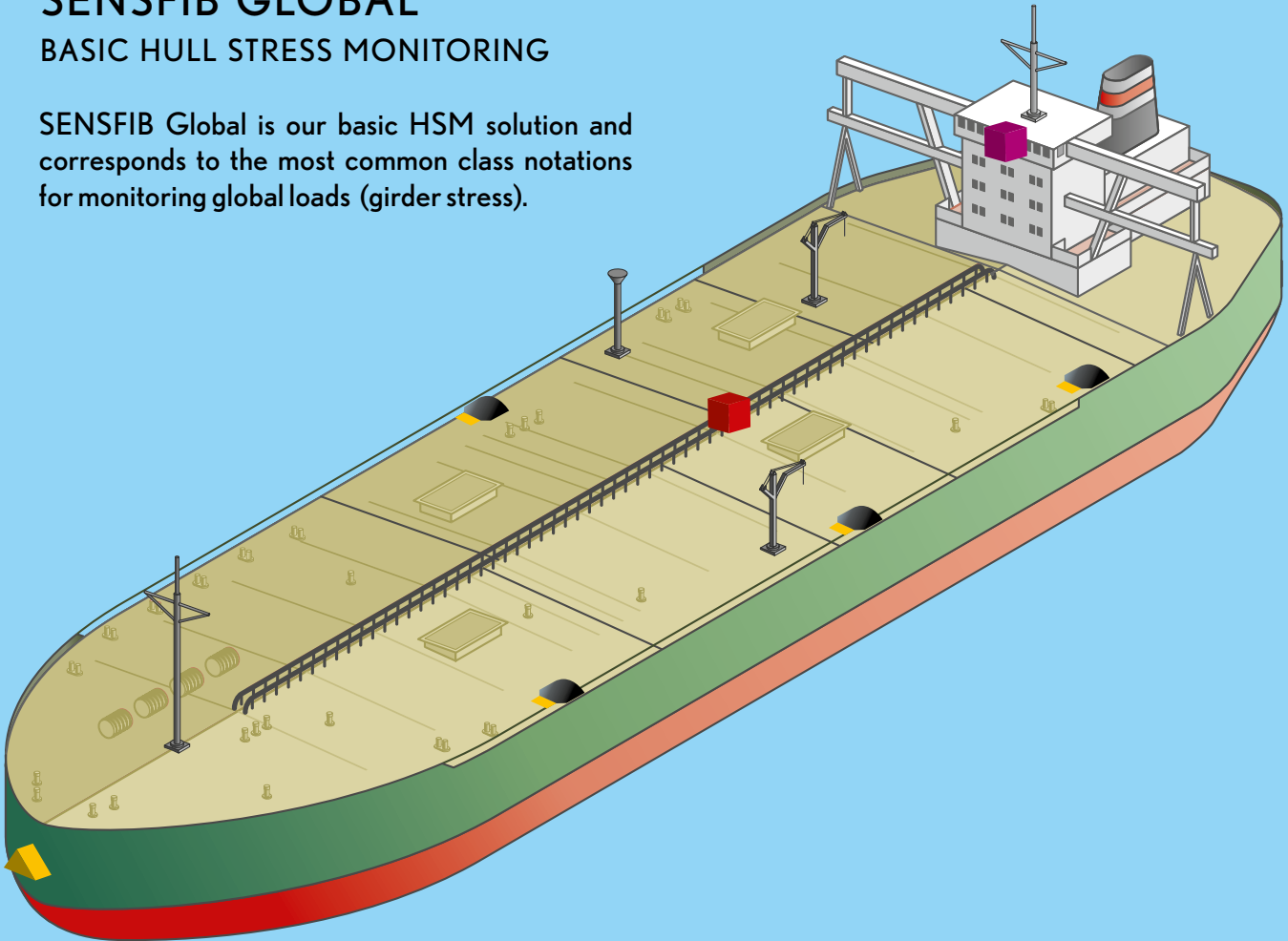


# CONFIGURATIONS

## SENSFIB GLOBAL

### BASIC HULL STRESS MONITORING

SENSFIB Global is our basic HSM solution and corresponds to the most common class notations for monitoring global loads (girder stress).



#### CLASS NOTATIONS

**SENSFIB Global can be configured for the following classes:**

- DNV HMON
- Lloyds Register ShipRight SEA
- Bureau Veritas MON-HULL
- ABS HM1 and HM2+R

**Software for onshore viewing of recorded data is available.**

#### STANDARD SCOPE OF SUPPLY

- 4 Fiber optic strain sensors
- 1 Fiber optic vertical accelerometer
- 1 TFT bridge display
- 1 PC with recording/backup facility
- 1 Uninterruptible Power Supply
- 1 A4 printer
- 2 Junction boxes
- 1 Fiber optic splice shelf
- Fiber optic cable

#### OPTIONS

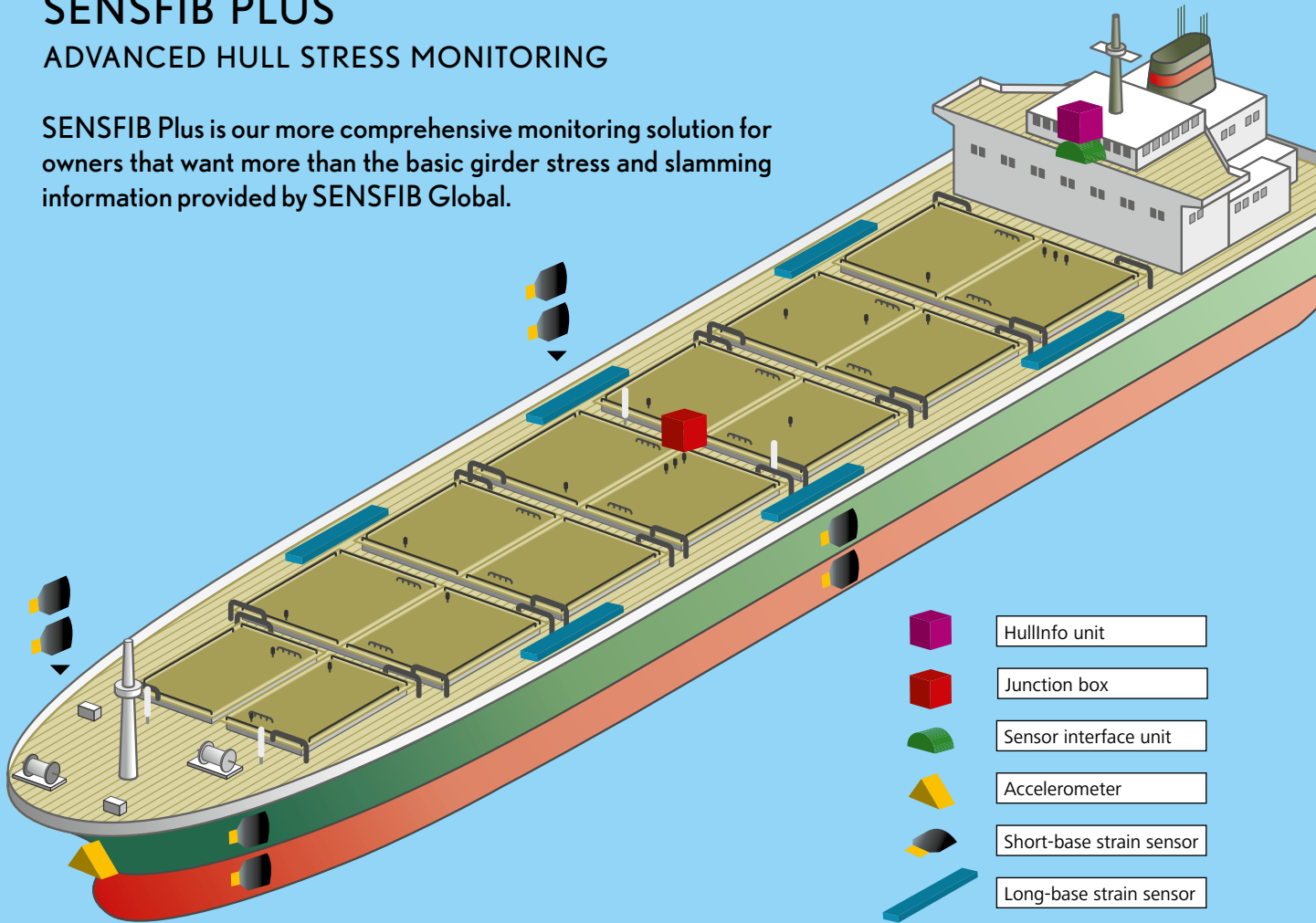
- Bow bottom slamming sensor
- 19" rack or cabinet
- Additional PC/TFT for remote display
- Onshore data viewer
- Interfacing to other systems, e.g.:
  - Loading computer
  - GPS
  - VDR
  - Ballast control



# SENSFIB PLUS

## ADVANCED HULL STRESS MONITORING

SENSFIB Plus is our more comprehensive monitoring solution for owners that want more than the basic girder stress and slamming information provided by SENSFIB Global.



### ADDED FUNCTIONALITY

**Examples of additional functionality that can be added to the SENSFIB Plus system includes:**

- Side shell fatigue monitoring with additional sensors in the waterline(s) amidships
- Slamming and ice response monitoring with additional sensors in the waterline in the bow
- Sloshing load monitoring on tank walls (for membrane type LNG-tankers)
- Design-specific sensors on innovative vessels
- Extended interfacing to other systems on-board and additional software modules for decision support

### SCOPE OF SUPPLY

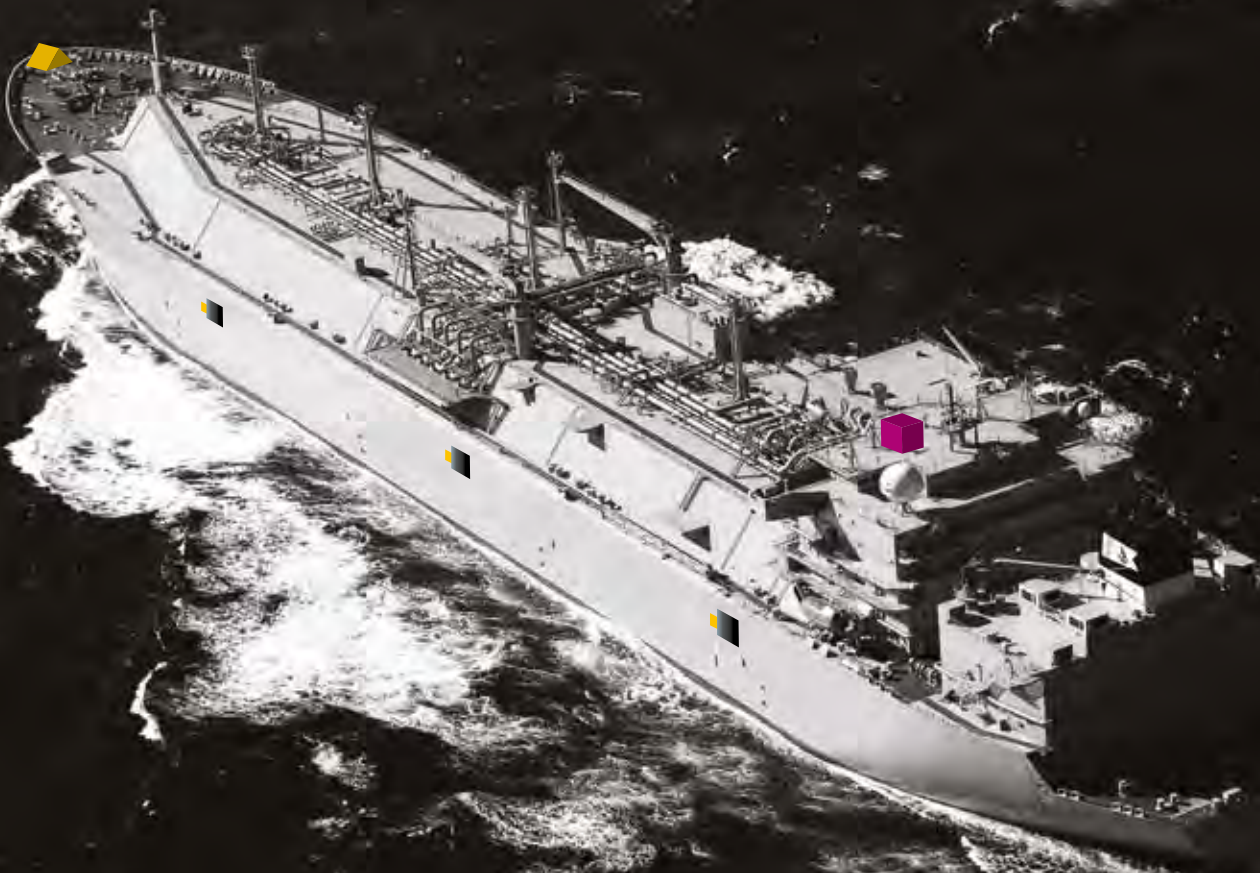
- 1 SENSFIB Global system
- 2–4 Side shell fatigue strain sensors
- 3–6 Bow/ice impact sensors
- 1–40 Sloshing load sensors
- 1– Ship design specific strain sensors

**Note that some configurations could require additional PCs and junction boxes.**

### OPTIONS

- Wave sensor
- 19" rack or cabinet
- Additional PC/TFT for remote display
- Interfacing to other systems, e.g.:
  - Loading computer
  - GPS
  - VDR
  - Ballast control

When a satellite link is available, the SENSFIB system can be configured to send short status reports and key data to shore by automatic e-mail at regular intervals.



# SYSTEM COMPONENTS



## Uninterruptible Power Supplies

**Maker:** GE / MGE UPS Systems

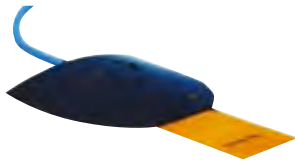
**Approvals/testing:** CE-marked, DNV type approval



## PCs and TFT monitors

**Maker:** Hatteland Display

**Approvals/testing:** DNV, GL, ClassNK, BV



## Fiber optic short-base sensor

**Maker:** Light Structures AS

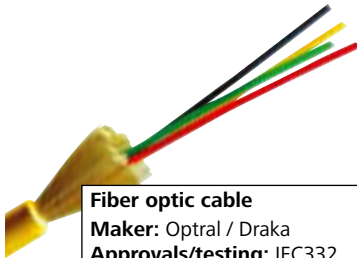
**Approvals/testing:** DNV type approval



## Fiber optic long-base sensor

**Maker:** Light Structures AS

**Approvals/testing:** Designed according to LR Rules.



## Fiber optic cable

**Maker:** Optral / Draka

**Approvals/testing:** IEC332, Low Smoke – Zero Halogen, metal free



## Signal receiver FBG Analyzer

**Maker:** Light Structures AS

**Approvals/testing:** IEC945, CE-marked, ATEX



## Fiber optic accelerometer

**Maker:** Light Structures AS

**Approvals/testing:** Qualified for marine use according to DNV Instrumentation and Automation.



## Optional printer

**Maker:** Hewlett-Packard



# TECHNICAL INFORMATION

## POWER

**Power Supply:** 230 VAC/50 Hz or 110 VAC/60 Hz

**Emergency power:** System supply via UPS with automatic switch from ship supply to internal battery pack on power failure. Minimum 10 minutes operation on backup power with automatic system shutdown after 10 minutes.

**Optical power:** < 1.0 mW per fiber

## VISUAL DISPLAY UNIT

**Size:** 15" or 17" TFT monitor

**Brightness:** Adjustable to zero

**Mounting:** Console or desktop mount

**Data backup:** CD/DVD-writer

**Interfacing:** Serial RS232/RS422 or Ethernet

## JUNCTION BOX

**Enclosure:** IP66

**Material:** AISI 316

## FIBER OPTIC CABLE

**Operating temperature:** [-25, 70] °C

**Oil resistance:** According to IEC 92-3

**Other:** Flame retardant, Halogen free, Metal free

## FIBER OPTIC STRAIN SENSORS

**Short-base sensor**

**Measurement range:**  $\pm 4000 \mu\text{m/m}$

**Accuracy (with FBGA):**  $2 \mu\text{m/m}$

**Frequency range:** 0–680 Hz

**Operating temperature:** [-25, 70] °C

**Temperature compensation:**

Built-in temperature sensor

**Enclosure:** IP68, 6 bar submersion

**Long-base sensor**

**Measurement range:**  $\pm 2000 \mu\text{m/m}$

**Accuracy (with FBGA):**  $2 \mu\text{m/m}$

**Frequency range:** 0–5 Hz

**Operating temperature:** [-25, 70] °C

**Temperature compensation:** Common mode rejection

**Enclosure:** IP65

## FIBER OPTIC ACCELEROMETER

**Measurement range:**  $\pm 20 \text{ m/s}^2$  (2 g)

**Accuracy (with FBGA):**  $\pm 0.1 \text{ m/s}^2$

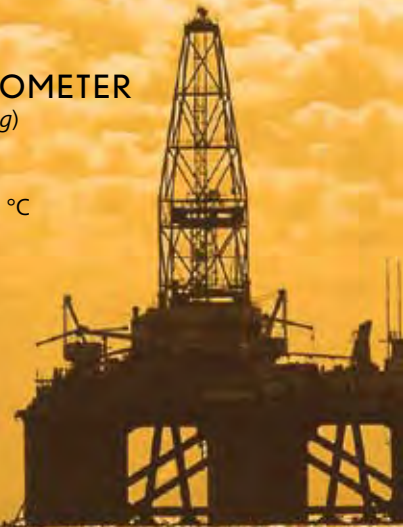
**Frequency range:** 0–100 Hz

**Operating temperature:** [-25, 70] °C

**Temperature compensation:**

Common mode rejection

**Enclosure:** IP66





# SUPPLEMENTAL PRODUCTS AND SERVICES

## ONBOARD SURVEY AND SERVICE

Although regular maintenance by an engineer is not required, it is of course available. We will despatch a system specialist from our head office in Norway to any port to provide the highest quality diagnostics, repair and service of systems.

## ONSHORE VIEWER SOFTWARE

A software package is available for reviewing data onshore. The data viewer mirrors the functionality of the onboard user interface, and allows browsing of backup data.

## DATA ANALYSIS AND MANAGEMENT

We can assist with onshore analysis of special events, and also copying, storing and retrieving backed up data.

## CONDITION REPORTS – SENSFIB VISTA

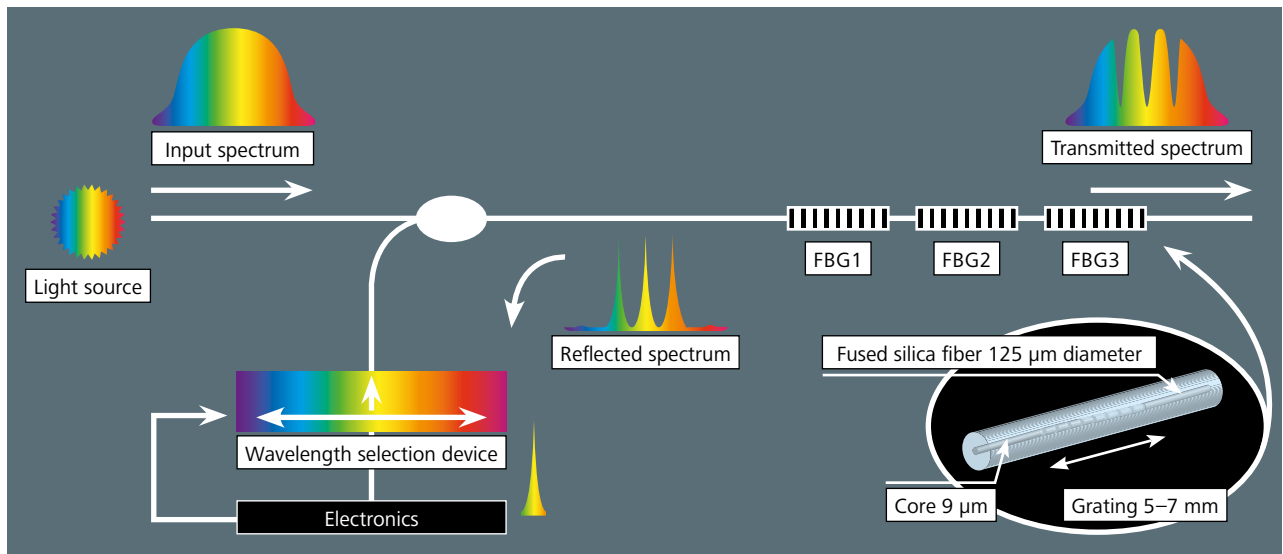
We offer a regular reporting service that includes a concise report of special events in the report period, fatigue status and history as a convenient input to the maintenance planner. This service requires that the ship forwards data backup to Light Structures at regular intervals.

## DECISION SUPPORT SYSTEMS

Contact us to learn more about how the Hull Stress Monitoring system can be extended to an advanced Decision Support system that provides guidance on what's on the horizon.

# PRINCIPLE OF FIBER BRAGG GRATING MEASUREMENTS

The SENSFIB Hull Stress Monitoring system is based on Fiber Bragg Grating (FBG) sensors. The FBGs are an internal stripe pattern in the core of the optical fiber that strongly reflects one wavelength (or color) of light.



The wavelength is determined by the period of the stripe pattern, which means that a strain or temperature that changes the period of the FBG can be characterized by monitoring the wavelength reflected from that FBG.

In a measurement system, a broadband light source illuminates the FBGs. A single peak wavelength is reflected from each FBG. The reflections are measured using a wavelength selection device that scans the spectrum. The temperatures and strains are then determined from the measured wavelengths.

As the illustration shows, more than one FBG can be coupled in series. This means that we can package sensors to measure more than one parameter. This is how Light Structures' strain sensors also measure the temperature at the sensor location.

The technique does not require much light to work well, so the optical power level can be kept very low, less than 1 mW. DNV has set an upper limit of 10 mW for intrinsically safe optical circuits.

# SENSIFIB Hull Stress Monitoring

Safer and more cost-effective operation through monitoring



Light Structures contributes to safer and more cost-effective operation of vessels and structures through the acquisition and analysis of load data. The company is the world leading provider of fiber optic monitoring systems to the maritime sector.

## SENSIFIB™

Safe and cost-effective operation of a vessel demands exact knowledge of the ship's design and awareness of the operation risks and their consequences.

Among these is the risk of ship encountering rough sea conditions where hull is subjected to significant stresses potentially leading to damage or, in the worst case, a disaster.

To avoid or mitigate hull damage induced by bending and slamming in waves, knowing the optimum heading and speed is crucial.

By continuously monitoring and analyzing stresses, the hull stress monitoring system can guide crew in crucial decision-making and provide alarms when stresses exceed safe limits. At the same time the system benefits ship owners by providing accurate information on the ship's operation and resulting fatigue damage.

Developed in cooperation with DNV class society and the Norwegian Defense Research Establishment, SENSIFIB is a hull monitoring system of choice for major shipyards in South Korea and throughout the world.



SENSIFIB interface and system components

Based on Fiber Bragg Grating sensor technology, SENSIFIB is a combination of fiber optic stress sensors, signal receiver and HULLINFO data processing and presentation software designed to provide operator on bridge with real-time feedback on vessel's operation.

SENSIFIB successfully benefits tankers, LNG carriers, bulk carriers, offshore ships and structures, container ships, cruise ships, navy and advanced hull design vessels.

SENSIFIB has been approved according to the hull stress monitoring rules of all major class societies - DNV HMON1 and HMON2, Lloyd's Register ShipRightSea, Bureau Veritas MON-HULL, ABS HM and RINA MONHULL.

### FIBER OPTIC ADVANTAGES

- *Explosion Safety.* No electric components and risk of sparks in hazardous areas
- *Reliability.* Robust design and long-term stability. Waterproof - no short circuits
- *Accuracy.* No electromagnetic noise and emissions. High signal precision and fast response over long distances
- *Cost Efficiency.* No sensor maintenance
- *Flexibility.* Small in size and weight. Easy to install with adhesives. Measure directly on stiffeners on dry surfaces or submerged in water in ballast tanks
- *Additional Functionality.* High multi-channel data throughput and multiple sensors on single cable. 2-in-one sensors for reading stress and temperature.

### SENSIFIB enables you to:

#### INCREASE SAFETY

- Protect your ship, crew and cargo
- Avoid environmental disasters
- Optimize heading and speed by knowing weather impact in real-time
- Know the limits for safe operation
- Document and verify hull performance
- Analyze failure (black box function)

#### SAVE COSTS

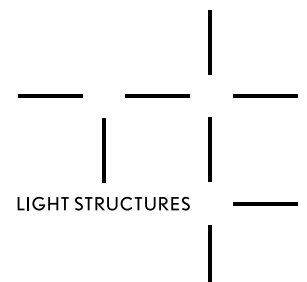
- Extend hull life and earning period
- Avoid unscheduled dry docking resulting from overloading damage
- Optimize maintenance to condition-based

#### IMPROVE COMPETITIVENESS

- Boost public image of safety awareness
- Receive additional Class notation to demonstrate ship's quality and safety

### SENSIFIB gives you overview of:

- Global hull girder stresses
- Local stresses in waterline
- Bow slamming
- Fatigue accumulation
- Whipping and springing
- Sloshing pressure in LNG tanks
- Ice response



Optimizing structure lifecycle.



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## **Appendix H Sh.A.M.An, CETENA**

(2 pages)

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## Sh.A.M.An. HULL MONITORING SYSTEM



CETENA has a long-standing experience on sea trials, long term monitoring, prediction of motions and stresses on sea-going vessels.

The availability of real time information on ship structures is an important support to safely protect ship asset, cargo and crew. CETENA has developed the **Ship Advanced Monitoring and Analysis (Sh.A.M.An.)** system able to reduce the risk of damage to hull structures caused by improper loading or high speed in bad weather conditions.

The system can be customized according to specific needs, integrating different kind of sensors like strain gauges, accelerometers, inclinometers, pressure gauges, wave radars and so on. Full 3D finite element analysis can be carried out by CETENA in order to choose the more appropriate location for sensors and set warning and alarm thresholds.

Sh.A.M.An. provides alarms in real time if hull stress overtakes thresholds and can be interfaced with most navigation equipments, automation systems, VDRs and loading computers. In particular, interfacing with the loading computer allows to compare predicted bending moment with data recorded by sensors on board in order to provide warnings or alarms and to control the loading operations.

The information collected by the software can be used to assist in hull condition evaluation and fatigue life assessment with the possibility to prevent structural cracks and to schedule inspections and maintenance activities.

Sh.A.M.An, can also be interfaced with ship maintenance software systems.

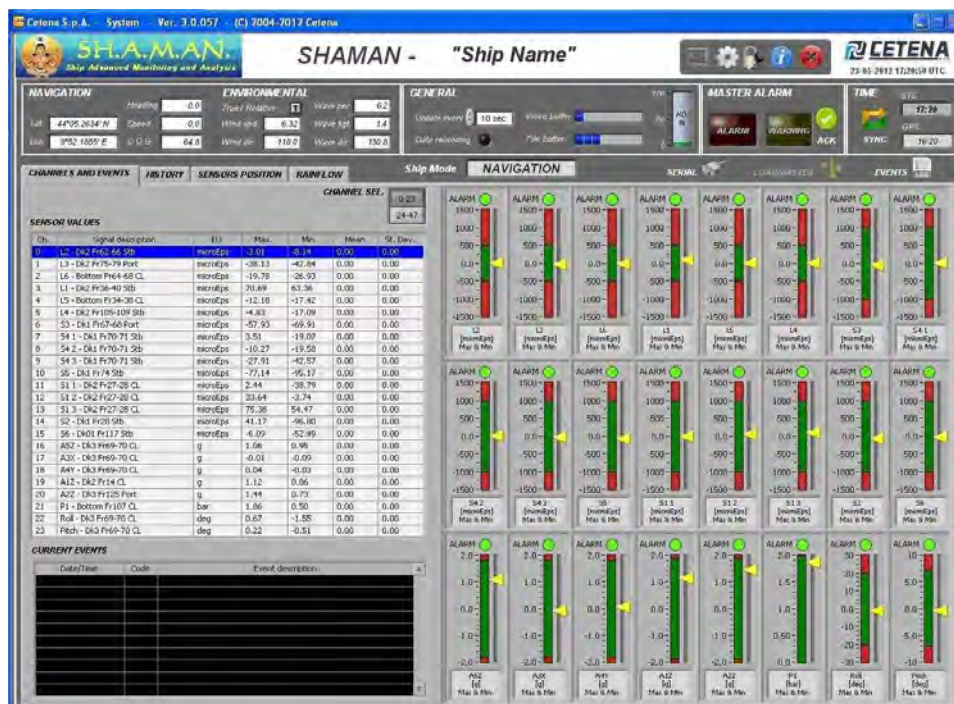
The system provides an opportunity for ship-owners to discuss and negotiate a lower insurance premium.

Sh.A.M.An. has recently been awarded the **Certificate of Design Assessment** by RINA according to the additional class notation MON-HULL + S.

## Configuration:

Sh.A.M.An. consists of:

- a set of sensors (strain gauges, accelerometers, inclinometers, pressure sensors, wave-meter or waveradar) for the detection of environmental conditions and ship's structures behaviour;
- one or more control units for data collection and processing;
- a console with a user-friendly graphical interface, to provide the ship Master and Officers with real time information on ship motions and loads, and a comparison with design data and threshold values.



## Benefits:

- Protects ship asset, cargo and crew;
- Helps to correct potentially dangerous situations;
- Monitors the ship structural integrity during transfer of ballast between different tanks at sea or in ship loading/unloading operations in port;
- Allows to evaluate and predict the ship fatigue life;
- Helps to understand how to best operate the ship, maintaining high structural safety margins;
- Reduces costs of any repairs due to damage of structures;
- Potentially reduces insurance premiums;
- Demonstrates the ship quality to charterers.

**For information: [SMO@cetena.it](mailto:SMO@cetena.it)**

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## **Appendix I   SMARTSTRESS, BMT SeaTech**

(5 pages)

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“Where will our knowledge take you?”

# Safety and Performance Monitoring SMART



# SMART

## (Ship-board Monitoring, Analysis and Recording Technologies)

### SMART

(Ship-board Monitoring, Analysis and Recording Technologies)

The **SMART** product suite comprises the following:

- **SMART<sup>STRESS</sup>** Hull Stress and Motion Monitoring;
- **SMART<sup>POWER</sup>** Ship Performance Monitoring;
- **SMART<sup>SHORE</sup>** Shore-side reporting and analysis of data.

The successful operation of a vessel depends upon a complex number of factors. Some will be totally within the ship owner's control and some, such as the weather, can only be forecast and attempts made to mitigate the impact.

In both respects, knowledge and an understanding of the risk and consequences are key to optimising a ship's performance and ensuring safe operation.



In conjunction with industry partners, ship operators and Masters, we have developed the **SMART** product suite, which is a range

of products that monitor and report on the safety and performance aspects of a ship's operation.

## Increased Safety through continuous monitoring

In heavy weather the safe operation of a ship requires decisions to be made regarding the optimum speed and heading to avoid excessive wave-induced bending and bow slamming.

**SMART<sup>STRESS</sup>** monitors hull stresses and motions in real-time, providing alarms to the ship's officers when the stresses exceed safe limits. By continuously recording these measurements, the system also provides the ship owner with accurate information on the ship's operation and resulting fatigue damage.

**SMART<sup>STRESS</sup>** utilises an easy-to-use touchscreen display and simple layout to provide the user with instantaneous access to vital information about the ship's current operating condition.

The system has been approved by all major class societies. The flexible design of **SMART<sup>STRESS</sup>** enables its configuration to be easily customised for bespoke monitoring applications, including the

option of fibre optic sensors.

**SMART<sup>STRESS</sup>** helps you to:

- protect your assets: hull, crew and cargo;
- determine the safe operating speed and heading in heavy weather;
- ensure the hull is not overstressed during ballast exchange at sea and cargo operations;
- reduce repair and off-hire costs resulting from heavy weather damage;
- help avoid or resolve charter disputes with accurate voyage reports of stresses, slamming and corresponding speeds;
- potentially reduce insurance premiums;
- demonstrate the quality and safety of your fleet to charterers (emphasised by Class notation);
- ensure your ship is operated within safe limits;
- extend the life of your ship through safer and strategic operational procedures.



# Cost Savings and Increased Efficiency

## through optimised performance

A vessel's operating efficiency is the sum of the engine, propeller and hull efficiencies. For a vessel to operate at its most economic, the prudent owner will wish to be able to quantify the effects of negative parameters on the performance, such as hull fouling, in order to optimise the period between hull or propeller cleaning.

**SMARTPOWER** is an advanced real time ship performance monitoring and analysis tool. Utilising touchscreen technology, the system continuously records ship speed, fuel consumption, shaft rpm and torque together with navigational and environmental parameters in order to present performance trends over time. These may be corrected for draft, trim and the environment.

Such knowledge can assist ship operators in:



- reducing emissions (CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>x</sub>);
- reducing fuel consumption;
- increasing operating speed;
- educating ship's staff in the factors effecting speed / fuel consumption;
- timely main engine repair / operation;
- optimising periods between hull and propeller cleaning;
- assessing alternative paint strategies.

## Improved Competitiveness

### through fleet comparison

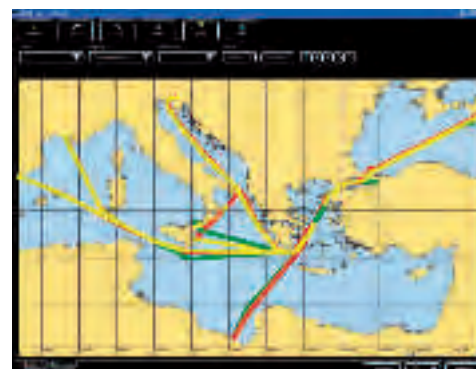
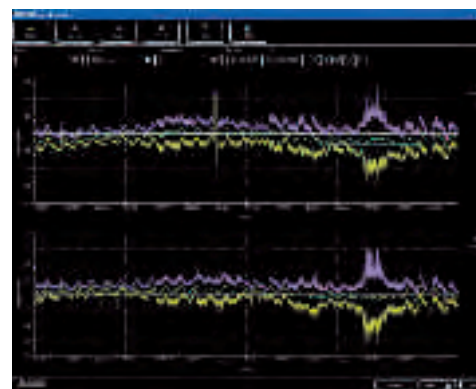
**SMARTSHORE** is a shore-based fleet performance and safety analysis tool. The software completes the suite of **SMART** products by providing the shoreside means to analyse data from ships fitted with BMT SeaTech's **SMARTSTRESS** and **SMARTPOWER** systems.

The simple design allows in-depth analysis to be performed on single or multiple vessel data simultaneously whilst also providing accurate report data for specific voyages or periods. In turn this allows the Superintendent or Ship Manager to identify opportunities for making performance or safety related decisions and providing the necessary feedback to the Master.

When used in conjunction with BMT SeaTech's Distributor emailing and network communications software, **SMARTSHORE** can automatically receive data from ships at regular periods such as daily or weekly so that information is constantly updated and analysed.

The versatility of the software allows user's to customise their own reports in order to suit the required analysis types and also export data in common file formats for use in spreadsheets or other applications.

A network license allows multiple users to access **SMARTSHORE** over a standard office network. The software can also be set up over a Wide Area Network allowing data analysis over the internet and complete access to vessel information.





**The BMT SMART product suite enables complete vessel safety and performance management. Monitoring hull stresses, motions, fatigue and performance characteristics means the ship operator can increase safe operation, reduce maintenance costs and improve performance, resulting in increased speed and reduced fuel consumption / emissions.**

**BMT SeaTech is a leading international provider of maritime products, advanced software systems and related specialist consultancy services to support commercial ship operations. BMT SeaTech's products and services enable customers to achieve outstanding operational performance and the highest safety standards. BMT SeaTech is a BMT Group company.**

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“Where will our knowledge take you?”

## Marine Safety and Compliance

### SMART Ship-board Monitoring, Analysis and Recording Technologies

#### SMART<sup>STRESS</sup>

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- Ensure the hull is not overstressed during ballast exchange at sea and cargo operations
- Reduce repair and off-hire costs resulting from heavy weather damage
- Help avoid or resolve charter disputes with accurate voyage reports of stresses, slamming and corresponding speeds
- Potentially reduce insurance premiums
- Demonstrate the quality & safety of your fleet to charterers (emphasised by Class notation)
- Know the safe operating limits of your ship more accurately
- Extend the life of your ship through safer and strategic operational procedures



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## **Appendix J   StressAlert, Strainstall UK Ltd**

(4 pages)

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**Straininstall UK Ltd are recognised as specialists and leaders in technical innovation and 'state of the art' technology. Our success in product development means that our customers benefit from proven engineering expertise.**

**Straininstall operates a quality management system which complies with the requirements of ISO 9001:2000.**



Certificate Number FM 12408

# StressAlert

HULL STRESS MONITORING SYSTEM

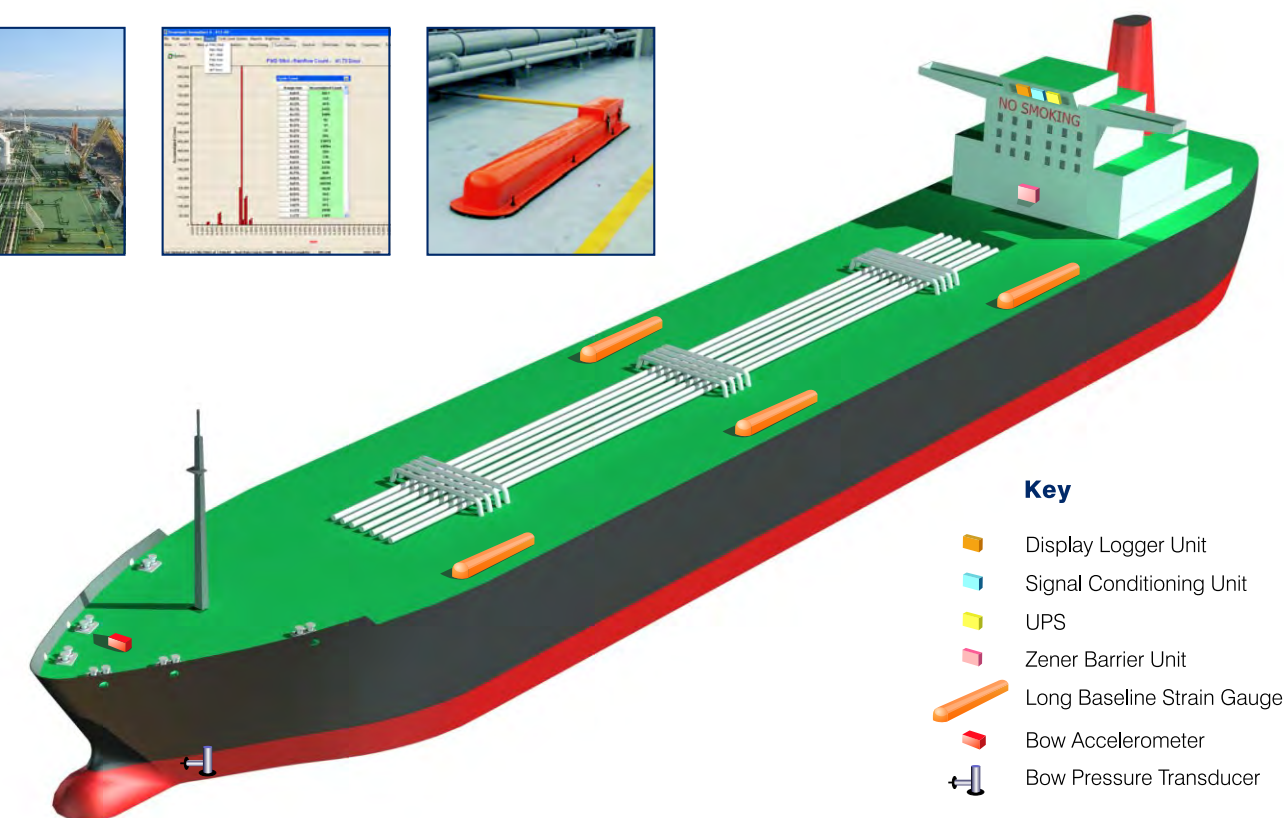


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 **Straininstall**

 **Straininstall**





- **Strainstall's StressAlert hull stress monitoring technology is the result of over 40 years at the leading edge of load measurement, strain and stress determination. This expertise, together with a strong commercial understanding of vessel operating control and safety, means that StressAlert is more than just an alarm system.**

Hull structural integrity is continuously monitored and displayed, and advanced algorithms contained within StressAlert enable predictions of hull status and deterioration to be determined. Course, speed and metocean information can be integrated within the standards packaged, giving increased safety and operational efficiency.

From an operational perspective, StressAlert enhances vessel safety due to a reduction in high stress incidences, enabling fuel savings and facilitating effective voyage management. The system provides instant access to the vessel's hull stress status, whether derived from dynamic wave action or induced stresses from cargo operations, allowing the ships master to alter course and speed to lower stress levels.

In some conditions a minor change of heading will result in significant reductions in stress levels without the need to reduce speed, and in other situations decreasing or increasing speed may be beneficial. During cargo operations, loading and discharging plans can be adapted to minimise the effects of structural stress.

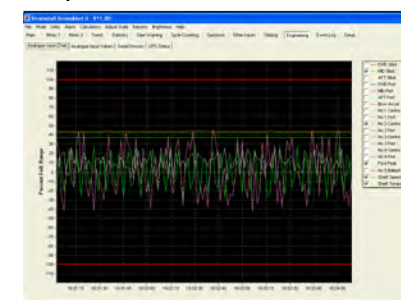


## Benefits

- **Demonstrates risk management**
- **Record of stresses allows the hull life to be maximised**
- **Detects early damage, cutting repair costs**
- **Can add to hull value on S&P market**
- **Can aid negotiations of dry-dock dispensations**
- **Improved charter rates**
- **Fuel savings**

**StressAlert can be configured to suit different vessel types and sizes to meet individual operating needs. Long baseline strain gauges, mounted on the deck or in holds (according to vessel type), measure structural bending. A bow accelerometer measures the impact of bow slamming and an optional bow pressure gauge measures dynamic bow draft.**

A range of display pages gives quick and easy access to all measured data. StressAlert uses mimic, trend and tabular displays as appropriate. All data is logged to provide a permanent record of vessel operations for post voyage analysis.



A signal conditioning unit interfaces and processes all sensor signals, and the inclusion of an optional zener barrier unit enables the sensors to be installed in hazardous areas. The system is also

fitted with an uninterruptible power supply (UPS) which provides operation in the event of ships power failure.

The standard system meets classification societies requirements such as Lloyds Register ShipRight SEA(HSS-4), American Bureau of Shipping HM2+R and Det Norske Veritas HMON and Bureau Veritas MON-HULL, and can be extended using additional sensors to meet higher specifications. Interfaces can also be provided to link with other ship systems, including navigation and environmental systems.

StressAlert has a remote display facility, enabling any PC connected to the ship's network to display all data and alarms from the main StressAlert system computer.

## Features

- **Links to navigation instrumentation and can automatically update the 'ships log' giving a full record of voyage data for later analysis.**
- **Installation is straightforward and usually carried out by shipyard personnel during vessel build or refit. Sensors are set-up and calibrated by Strainstall engineers, or approved agents throughout the world.**
- **Meets the requirements of all the major classification societies around the world.**
- **Meets the requirements of all the major classification societies around the world.**



## StressAlert - Hull Stress Monitoring

- ▶ More than 100 systems in service
- ▶ Monitors static and dynamic forces on the vessel during loading, unloading and at sea
- ▶ Helps define limits of operation of the ship
- ▶ Maintains a continuous, permanent record of forces on the vessel structure
- ▶ Increases value on the S&P market by recording risk management data
- ▶ Enables safer operation of the vessel



### Description

StressAlert is a hull stress monitoring system for a large range of ships, including FPSOs, oil and LNG tankers, bulk carriers and container ships. It provides advanced monitoring of structural integrity throughout the life of a vessel, and enables the Master to pilot his vessel to the maximum safe efficiency.

The system monitors bow slamming and the longitudinal bending movements within the structure, and compares these with levels predetermined by the classification society in conjunction with the naval architect or ship designer. Time histories and alarms are displayed on a comprehensive set of screen displays, and interfaces to other on-board systems are provided.

StressAlert is built to meet requirements for electrical apparatus operating in hazardous areas and is approved by marine classification societies. The basic system meets classification societies' requirements such as Lloyds Register ShipRight SEA(Hss-4), Det Norske Veritas HMON-1 and American Bureau of Shipping HM2+R. Additional sensors are available to meet higher specifications required by some classification societies' notations, such as DNV HMON-2 and ABS Hm3.



# StressAlert - Hull Stress Monitoring

## Typical Installation

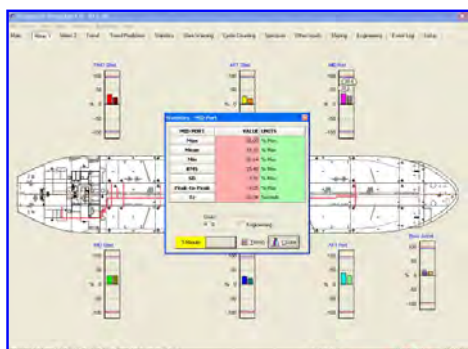
- 4 x Long baseline strain gauges
- 1 x Bow accelerometer
- 1 x Bow pressure transducer (optional)
- 1 x Zener barrier unit
- 1 x Logger/Display unit - PC
- 1 x Signal conditioning unit
- 1 x Uninterruptible power supply unit
- 1 x Printer (optional)



Deck gauge



Accelerometer



Screen display's



StressAlert can be installed and commissioned on new-builds, or as retrofit, by our team of field engineers and trained representatives world-wide.

Issue No. 1

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## **Appendix K *Narada* Wireless Data Acquisition and Control System**

(1 pages)

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# NARADA

## WIRELESS DATA ACQUISITION AND CONTROL SYSTEM



### OVERVIEW

The Narada system is a powerful wireless data acquisition and control solution built around the Atmel ATmega128 microcontroller. Designed for applications requiring high resolution data collection, and/or real-time control, the Narada has a four-channel 16-bit ADC and 128kB of supplemental SRAM for temporary data storage. Unique amongst its competitors, the Narada also incorporates a two-channel 12-bit DAC for wireless control applications.

By leveraging the versatile TI CC2420 wireless radio for IEEE 802.15.4 communications and an optional high-gain radio for extended range, the Narada system is capable of reliable data transmission in large networks and at distances of up to 600m.

An extensive software development kit is also available for purchase with the Narada hardware. This kit contains tools to help create intelligent software solutions for both the embedded and the PC environment that are applicable to a variety of sensing and controls applications.

| CPU                  |                 |
|----------------------|-----------------|
| Processor            | Atmel ATmega128 |
| FLASH                | 128 kB          |
| EEPROM               | 4 kB            |
| SRAM                 | 4 kB            |
| External SRAM        | 128 kB          |
| External Clock Speed | 8 MHz           |

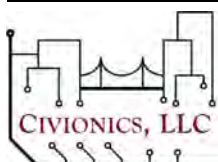
| DATA ACQUISITION             |                                 |
|------------------------------|---------------------------------|
| Input Channels               | 4 Single Ended / 2 Differential |
| Analog-to-Digital Conversion | 16-bit Resolution (0 - 5 V)     |
| Data Storage Capacity        | 128kB (> 60,000 data points)    |
| DC Sensor Excitation         | +5 V DC                         |
| Real-Time Data Throughput    | 1,500 samples / sec             |
| Maximum Sampling Rate        | 10,000 samples / sec            |

| GENERAL INFORMATION           |   |
|-------------------------------|---|
| Dimensions                    | 69mm x 72mm x 12mm<br>(with standard radio) |
| Base Station to PC Interfaces | RS-232, USB                                 |

| VOLTAGE ACTUATION            |                             |
|------------------------------|-----------------------------|
| Output Channels              | 2                           |
| Digital-to-Analog Conversion | 12-bit Resolution (0 - 4 V) |
| Maximum Output Current       | 15 mA                       |

| RADIO                 |  |
|-----------------------|--|
| Transceiver           | TI CC2420                                      |
| Frequency Band        | 2.4000 - 2.4835 GHz                            |
| Data Rate             | 250 kb/s                                       |
| Range (line of sight) | 50m (standard radio)<br>600m (high gain radio) |

| POWER CONSUMPTION           |                |
|-----------------------------|----------------|
| Current Draw in Sleep Mode  | 10 mA          |
| Current Draw in Active Mode | 30 mA          |
| Current Draw in Rx/Tx Mode  | 52 mA          |
| Input Voltage               | 6.0 - 9.0 V    |
| Batteries                   | 5/6-AA or 1-9V |



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Narada hardware design licensed from the University of Michigan



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| 19. ABSTRACT<br>At the request of DMO Head Maritime Systems Division (HMSD) a study was undertaken to investigate issues related to installation of hull structural monitoring systems (HSMS) on RAN ships. This report provides results of a literature and internet survey to determine the state of the art of HSMS on commercial and military ships together with discussion of issues related to navy ships generally. System configurations range from basic installations intended to monitor hull girder bending stresses up to complex developmental systems employing technologies such as fibre-optic sensors and wireless data transmission. Vendor material related to commercial off the shelf (COTS) systems is provided in a number of appendices. |  |                             |  |   |   |                              |  |                             |  |